WHEAT FLOUR TORTILLA: QUALITY PREDICTION AND STUDY OF PHYSICAL AND TEXTURAL CHANGES DURING STORAGE

A Thesis

by

FREDERICO AUGUSTO RIBEIRO DE BARROS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2009

Major Subject: Food Science and Technology

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ABSTRACT

Wheat Flour Tortilla: Quality Prediction and Study of Physical and Textural Changes during Storage. (May 2009)

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Chair of Advisory Committee: Dr. Lloyd W. Rooney

A cost-effective, faster and efficient way of screening wheat samples suitable for tortilla production is needed. Hence, we developed prediction models for tortilla quality (diameter, specific volume, color and texture parameters) using grain, flour and dough properties of 16 wheat flours. The prediction models were developed using stepwise multiple regression.

Dough rheological tests had higher correlations with tortilla quality than grain and flour chemical tests. Dough resistance to extension was correlated best with tortilla quality, particularly tortilla diameter ($r= -0.87$, $P<0.01$). Gluten index was significantly correlated with tortilla diameter ($r = -0.67$, $P<0.01$) and specific volume ($r = -0.73$, $P<0.01$).

Tortilla diameter was the parameter best predicted. An r^2 of 0.87 was obtained when mix-time and dough resistance to extension were entered into the model. This model was validated using another sample set, and an r^2 of 0.91 was obtained.

Refined and whole wheat flours, dough and tortillas were compared using five wheat samples. Refined flour doughs were more extensible and softer than whole wheat flour doughs. Whole wheat flour tortillas were larger, thinner and less opaque than

refined flour tortillas. Refined wheat flour had much smaller particle size and less fiber than whole wheat flour. These are the major factors that contributed to the observed differences. In general, refined wheat tortillas were more shelf-stable than whole wheat tortillas. However, whole wheat tortillas from strong flours had excellent shelf-stability which must be considered when whole wheat tortillas are processed. .

Different objective rheological techniques were used to characterize the texture of refined and whole flour tortillas during storage. Differences in texture between 0, 1 and 4 day-old tortillas were detected by rupture distance from one and two-dimension extensibility techniques. In general, the deformation modulus was not a good parameter to differentiate tortilla texture at the beginning of storage. It detected textural changes of 8 and 14 day-old tortillas. The subjective rollability method detected textural changes after 4 days storage.

DEDICATION

To my parents Geraldo and Maria de Fatima, to my siblings Fabricio and Fabiana

and

To my fiancée, Lilian.

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CHAPTER I

INTRODUCTION

Good quality tortillas are symmetrical, uniform and opaque with toasted spots. They should also be soft, flexible without cracking when folded, and puffed (Waniska 1999). Good quality wheat flour tortillas usually have large diameters (17-18 cm) and more than two weeks of shelf stability (Pascut et al 2004).

Every year breeders screen many wheat lines to find suitable wheat for tortilla production. Currently, this is done by processing the wheat samples into tortillas, which is a time-consuming and costly process. Finding predictors to estimate outstanding tortilla quality is an approach that will save time and money eliminating undesirable samples at an earlier stage in breeding programs.

Various researchers have attempted to predict bread quality (bake mix time, bake water absorption and loaf volume) by taking measurements of grain, flour or dough properties and combining them into prediction models (Dowell et al 2008; Razmi-Rad et al 2007; Lee et al 2006; Millar 2003; Andersson et al 1994). Dowell et al (2008) combined up to 50 parameters and found that flour protein content was the best predictor for loaf volume whereas bake mix time was best predicted using mixograph mix time. They also mentioned that the model to predict loaf volume could be improved by adding measures of dough strength and viscoelastic properties.

This thesis follows the style of *Cereal Chemistry*.

For tortillas, flour characteristics, and/or dough and gluten rheological properties may provide predictors. In the food industry rheological evaluations are used to determine raw material characteristics, processing parameters and final product characteristics. Rheological measurements are used at numerous points in the development of new products and processes, during process optimization, quality control, shelf life testing and evaluating food texture by correlation with sensory data.

Dough is the intermediate product in the production of tortillas from wheat flour. It exhibits elastic and viscous flow properties so rheological properties of dough are important. They determine its behavior during dividing, rounding and molding, as well as the quality of the finished products.

Dough is a complex system because of different ingredient interactions such as protein-protein, starch-protein and starch-starch which contribute to the rheological behavior. Therefore, studying only gluten could simplify the system and facilitate the interpretation of rheological tests (Schober et al 2002). Currently, no prediction studies have used a Texture Analyzer to evaluate rheological properties.

Many studies with objective texture evaluations using a texture analyzer, and subjective tests of wheat flour dough and tortillas have been conducted. Some authors evaluated the effects of additives (Friend et al 1993; Suhendro et al 1995), enzymes (Alviola et al 2008; Guo et al 2003), wheat starch and gluten (Wang and Flores 1999a), and effect of replacing part of the wheat flour with decorticated sorghum flour (Torres et al 1994) on dough and tortilla rheological properties.

Waniska et al (2004) used 61 commercial tortilla flours to study tortilla qualities, but they did not do any textural analysis. The only objective rheological method used was the mixograph test to estimate dough mixing properties. Srinivasan et al (2000) studied the effect of ingredients and processing on dough rheology of wheat flour tortillas primarily using objective texture analysis tests. They also determined the relationships between objective dough evaluations and tortilla characteristics. However, they did not create any prediction model, and they used only one type of wheat flour, eliminating the possibility of studying how flour characteristics could affect tortilla quality.

Shelf stability is an important part of tortilla quality, thus the need to determine texture changes during storage of flour tortillas. Bejosano et al (2005) compared different objective rheological methods and sensory evaluation to study loss of tortilla flexibility. Since their research was conducted using only one wheat flour, it is not possible to draw strong conclusions. Diversity of flours is important in evaluating objective texture measurements to provide more reliable results. Similar work was done in corn tortillas (Suhendro 1997; Ucles 2003; Limanond 2000) wherein objective rheological methods were used to monitor texture changes over time.

Improving tortilla's nutrition profile also means quality enhancement. Many food industries are using whole grain flour in their products due to the increasing demand for healthier products. Only a few papers on whole wheat flour tortillas were found. Friend et al (1992) studied the quality and acceptability of whole wheat flour tortillas and compared them with refined wheat flour tortillas. They showed that whole wheat tortillas are a good source of dietary fiber; however, tortillas prepared with refined wheat flour had higher acceptability compared to whole wheat tortillas, which also had poorer dough machinability and decreased storage stability. Their study only determined physical and sensory properties, and shelf-stability using a subjective rollability test. Characterizing the rheological and physical properties of whole wheat flour tortillas is very important to better understand this product as a starting point for other studies.

This project was divided into two parts, and the objectives were:

Part I

1. Improve/Optimize rheological methods for dough and gluten using a Texture Analyzer.
2. Investigate relationships between flour characteristics, dough and gluten rheological properties, and tortilla quality.
3. Develop prediction models for tortilla quality that may help wheat breeding programs and the food industry to determine high-quality wheat for tortilla production.
4. Validate the prediction models.

Part II

1. Characterize refined and whole wheat flour doughs and tortillas prepared from different flours using physical and rheological methods.
2. Choose the most appropriate rheological method or methods to measure tortilla shelf-stability.

APPROACH

In the first part of this research, objective rheological methods using a Texture Analyzer were evaluated. Different dough and tortilla samples were prepared to see if the methods could differentiate between them. Methods and their setups that gave reliable and reproducible results were chosen for all tests done throughout this research.

Tests to find tortilla quality predictor (s) from grain and flour characteristics and dough/gluten rheological properties were evaluated. In the first stage, these variables were correlated with tortilla quality to screen high and low correlated independent variables. Subsequently, multiple linear regression analyses were done to find the independent variable(s) which explain the tortilla quality variables the best.

In the second part of this research, objective techniques using a texture analyzer and subjective rollability were used to compare shelf-stability of refined and whole wheat flour tortilla over 14 days of storage. Moreover, texture analyses were used to compare dough rheology of refined and whole wheat flours.

CHAPTER II

LITERATURE REVIEW

WHEAT FLOUR AND DOUGH

Wheat flour is the major ingredient in wheat flour tortilla production, accounting for 80-95% of the dry matter. Its characteristics determine tortilla quality. Better quality tortillas are prepared from hard wheat flour with intermediate protein content (Waniska et al 2004; Guo et al 2003). Generally, enriched, bleached, hard wheat flour is used to make flour tortillas (Serna-Saldivar et al 1988).

When wheat flour is mixed with water, viscoelastic dough is formed. Due to this unique characteristic, wheat flour can be processed into a variety of food products such as bread, biscuit, tortillas and pasta, among others.

Investigations on flour and dough characteristics have been conducted using analytical physico-chemical methods and also flour performance tests including Farinograph, Mixograph, Extensigraph and Alveograph tests (Atwell, 2001). According to Srinivasan (1996), the rheology of dough is affected by the interactions of gluten proteins and other flour components. This viscoelastic behavior emerges only after the proteins interact with other components in the dough.

Flour-water interactions are the most important reaction within a dough system. If an insufficient amount of water is added to meet the hydration needs of all dough components, the gluten does not become fully hydrated and the elastic behavior of the dough is not fully developed. On the other hand, if water is added in excess, the viscous component in the dough is dominant, and the dough shows decreased resistance to extension, increased extensibility and development of a sticky dough (Srinivasan, 1996). The increase in water content weakens the elastic properties of gluten by decreasing the number of cross links (Belitz et al 1986).

GLUTEN PROTEINS

The viscoelastic behavior of wheat dough can be attributed to two types of storage proteins: prolamin (gliadin) and glutelin (glutenin). When water is added and mixing occurs, these two proteins form a network known as gluten which gives the dough unique rheological properties (Shewry and Halford 2002).

Glutenins

They are among the largest protein molecules in nature. Glutenins are heterogeneous mixtures of polymers formed of polypeptides linked by disulfide bonds. These polypeptides are divided into four groups: The A-group is named high molecular weight glutenins subunits (HMW-GS) while the groups B, C and D are named low molecular weight glutenin subunits (LMW-GS). The LMW-GS are present in a much higher concentration than HMW-GS. Polypeptides from all of these groups are post-translationally linked by disulfide bonds to form the heterogeneous aggregates known as polymeric glutenins (Gianibelli et al 2001).

The structure of the polymeric molecules is responsible for their functionality (MacRitchie 1992). Several models have been proposed to explain their structure. There is a general agreement that the polymers containing LMW-GS and HMW-GS are formed in a random or quasi-random manner (Gianibelli et al 2001). The amount of HMW-GS polymers is essential in determining dough quality. The size distribution of the polymers is very important as well (Southan and MacRitchie 1999).

Gliadins

Gliadins are monomers, and form a heterogeneous mixture of polypeptides soluble in 70% aqueous alcohol. Gliadins can be divided into four groups: α-, β-, γ- and ω- gliadins. This classification of gliadins is useful since these are valid groups in terms of their structural and genetic relationships (Shewry 2003).

Gliadins are considered to contribute to gluten viscosity as plasticizing elements, and to gluten extensibility (Gianibelli et al 2001) while glutenins contribute to the elasticity and strength of the dough, giving the dough its property of resistance to extension (Hoseney 1994; Smewing 1995).

WHEAT FLOUR TORTILLA TECHNOLOGY

Wheat flour tortillas are unfermented flat breads. Tortillas were traditionally homemade and widely consumed in northern Mexico for centuries; their popularity is increasing in the United States (Guo et al 2003). Tortillas are usually consumed after they have been stored in the US. However, consumers expect tortillas to maintain their shelf stability (flexibility) and shelf life (microbial) for weeks (Cepeda et al 2000; Waniska et al 2004).

Tortillas are produced by hot-press, die-cut or hand-stretch procedures. In hot-press tortillas the baking temperature is lower but they have longer oven dwell times than the other procedures. They resist moisture absorption from the fillings. They are smoother, more elastic, and resistant to tearing and cracking. Die cut tortillas have lower moisture content, less elasticity, higher density, and reduced resistance to cracking. Hand-stretch procedure is the most labor intensive and requires more sanitation and maintenance. These tortillas have an irregular shape and intermediate quality (Guo et al 2003; Serna-Saldivar et al 1988).

Tortillas hold a variety of fillings and are used as tasty food scoops, toasted and topped with salads and other ingredients as finger or hand foods. Many different types of wheat flour tortillas are marketed such as low-fat, low carbohydrates and whole wheat flour tortillas (Alviola 2008).

Whole wheat flour tortillas are an important source of dietary fiber and micronutrients such as minerals and vitamins. The regular consumption of whole grains and whole grain products is associated with reduced risk of various types of chronic diseases. Whole grains are rich sources of fiber, vitamins, minerals, and phytochemicals (Liu 2007). The phytochemicals found in whole grains are unique and they complement those found in fruits and vegetables.

WHEAT FLOUR TORTILLA INGREDIENTS

Water acts as a medium for ingredient incorporation and is responsible for the formation of the gluten complex. The amount used is from 45 to 55% depending on the flour type, process and other ingredients (Serna-Saldivar et al 1988).

Shortening improves dough machinability. It acts as a lubricant and interacts with proteins and starch during mixing, baking and cooling. It increases shelf life and decreases staling. From 5-15% of shortening is used to make wheat flour tortillas (Serna-Saldivar et al 1988).

Most formulations contain 1.3 to 2% of salt. It makes the dough less sticky because it strengthens and toughens the gluten by shielding charges on the dough proteins. It is also responsible for the tortilla flavor and shelf life (Serna-Saldivar et al 1988)

Leavening agents such as sodium bicarbonate and sodium aluminum sulfate are used from 1 to 2% in wheat flour tortilla formulations. Tortillas have a whiter appearance due to a change in texture, density and color. A pH from 5.5 to 6 is recommended to produce optimum color, leavening action and improve the effectiveness of preservatives (Serna-Saldivar et al 1988).

Emulsifiers are used to improve dough machinability and tortilla texture. Sodium stearoyl-2-lactylate (SSL), monoglycerides and diglycerides are the ones most used in the tortilla industry (Serna-Saldivar et al 1988).

The preservatives sodium and calcium propionates and potassium sorbates are commonly used alone or in combination to extend tortilla shelf life (Serna-Saldivar et al 1988).

Reducing agents, L-cysteine or bisulfites are added to improve dough machinability by increasing the extensible component and decreasing elasticity. They inhibit or prevent the formation of disulfide bonds between protein chains (Serna-Saldivar et al 1988).

FACTORS THAT AFFECT TORTILLA QUALITY

Monitoring tortilla quality, as indicated by diameter, opacity and firmness, is a very important task in tortilla production. Tortilla staling for example is identified by a gradual decrease in rollability, a gradual increase in firmness, and a more brittle structure, rendering the product unacceptable to consumers (Friend et al 1993). According to Seetharaman et al (2002) and Bejosano et al (2005), tortilla firmness increased over time.

Although amylopectin is considered to play the most important role in staling (Gray and BeMiller 2003), other factors also affect tortilla quality such as amylose content and damaged starch (Waniska et al 2002, Mao and Flores 2001). The enzyme α-amylase improved shelf-stability of wheat flour tortillas by retarding staling (Alviola and Waniska 2008).

Protein content and gluten also affect tortilla quality. Wheat flours with higher protein produce more shelf-stable tortillas (Suhendro et al 1995). Addition of 2-3% vital wheat gluten improved strength of dough, and shelf-stability of wheat flour tortillas (Suhendro et al 1993).

According to Srinivasan et al (2000), ingredients (fat, gluten, water and cysteine) and processing conditions (dough mixing and temperature) change dough and tortilla properties. They concluded that ingredients were the major cause for this change. Less fat, less cysteine, less water and/or more gluten increased the solid-like properties of dough (elasticity).

SUBJECTIVE METHODS TO EVALUATE WHEAT FLOUR DOUGH AND TORTILLAS

Wheat flour dough is evaluated subjectively for smoothness, softness, extensibility, force to extend (elasticity) and press rating (force required to flatten dough) (Alviola et al 2008).

The subjective rollability method is most commonly used to evaluate textural changes in wheat flour tortillas during storage (Suhendro et al 1999, Srinivasan 1996). The ability of tortillas to be rolled is a direct indication of their quality. It is a simple method and reflects the way tortillas are handled before consumption. However, the rollability score can be different from person to person, and it is not sensitive enough to monitor changes in tortilla texture within 24 hours after baking.

RHEOLOGICAL METHODS

Rheology is the science of deformation and flow of matter. A viscous deformation can be explained if the applied force causes a permanent deformation of the material. If the deformed surface returns to its initial state, it is an elastic deformation (Steffe, 1996). According to this author, “dough is probably the most complex material facing the food rheologist”.

An important requirement for the production of uniform baked foods is an adequate control over the composition and functional properties of the ingredients used in the process. To meet these requirements, a number of analytical procedures are done in the bakery’s quality control laboratory including rheological methods.

The baking industry uses a variety of objective methods to characterize the rheology of wheat flour dough and final products. Those objective procedures imitate subjective measurements, and are sensitive and reliable. Objective texture measurements characterize the rheology of wheat flour dough and tortillas (Srinivasan 1996; Bejosano et al 2005). Rheological methods are divided in three categories: empirical, imitative and fundamental.

Empirical

Empirical rheology has many advantages over fundamental rheology. Empirical methods are usually easy and fast to perform, making them practical to use and less expensive. The disadvantages are the impossibility of describing results in terms of fundamental rheological properties, since the methods do not involve the measurement of well-defined quantities but are limited to providing empirical correlations (Bourne 2002).

Many types of equipment have been developed for empirical rheological testing. Brabender farinograph and mixograph are used to study mixing properties by measuring factors such as dough development time or water absorption. Brabender extensigraph and the Chopin alveograph are used to determine extensional properties like resistance to extension and extensibility (Bourne 2002).

Equipment very often used in food industries for textural determinations is the Texture Analyzer (Texture Technologies, Scarsdale, NY/Stable Micro Systems, Godalming, Surrey, UK). It has a user-friendly computer interface which enables results to be stored, manipulated and compared with previous or future tests.

SMS/Kieffer dough and gluten extensibility rig

Kieffer et al (1998) developed this micro-scale method to measure extensibility in dough and gluten. This rig has been developed by Stable Micro Systems for use with the TA.XT2/TA.XTPlus/TA.HDPlus texture analyzer. Common methods of measuring the extension behavior of dough or gluten are to extend the dough between fingers or use the extensigraph/alveograph. The extensibility rig used on the texture analyzer gives accurate and objective results in a graphical format. A hook probe extends a small cylindrical dough sample until it ruptures. The peak force is measured as the resistance to extension (elasticity) in Newton and the distance at which the dough strip ruptures is measured as extensibility (Smewing 1995; Srinivasan 1996).

Micro-extension tests provide a reliable prediction of bread quality, and are useful to study the influence on extension properties of gluten components (Kieffer et al 1998; Wieser et al 2000). These tests have also been used to develop rheological dough models (Gras et al 2000). Dough extension methods based on texture analyzers have been proposed for use in breeding program screening for discriminating between wheat varieties on a molecular basis and assessing baking performance (Bekes et al 2001; Anderssen et al 2004).

Tensile strength technique

Pulling a material at each end causes the material to rupture completely. A uniaxial or 1-D tensile test has been used to evaluate tensile characteristics of products (Suhendro 1997). This author used this method to evaluate corn tortilla texture. Fresh tortillas were soft with a lower force and modulus of deformation during the test, requiring longer time and greater distance prior to rupture. As storage time increased, the rupture force and modulus of deformation increased; rupture distance decreased. These finding are consistent with those of Bejosano et al (2005), who found that the one-dimensional extensibility test detects changes in texture of wheat flour tortillas during storage.

Two-dimensional extensibility technique

The principle of this method involves measuring the force required to push a probe into a food indicating the force required to rupture the product and its extensibility. This technique has been used to evaluate the hardness/firmness of breads and nixtamalized corn masa. Bejosano et al (2005) and Suhendro (1997) have also used this test to study the changes in texture of wheat flour tortillas and corn tortillas, respectively, over storage time. Alviola et al (2008) also used this technique to evaluate the effect of protease and transglutaminase (TG) on tortilla texture.

Imitative tests

Imitative tests use instruments to imitate the conditions in which the food is used in practice (Bourne 2002).

Texture profile analysis (TPA)

TPA was developed to imitate mastication expressed by a force-time curve. Many parameters can be measured including hardness, adhesiveness, cohesiveness and springiness. This technique has been applied for cheese, apples, noodles, pasta and masa; it has a good correlation with sensory analysis methods (Bourne 2002). The TPA test was a good indicator of masa hardness (Bosiger 1997) and determined the effect of ingredient composition and processing parameters on wheat flour dough properties (Srinivasan 1996).

Fundamental tests

Fundamental tests are used to measure material properties that are independent of the instrument on which they are measured meaning that different instruments will produce the same results. Fundamental tests generally assume small strains (1-3% maximum) and the material is homogeneous. Those tests are generally slow to perform, do not correlate as well with sensory methods as empirical tests do, require expensive equipment that is difficult to maintain in an industrial environment and require high levels of technical skill. The most common types of fundamental tests used in cereal research are small deformation dynamic shear oscillation and small/large deformation shear creep and stress relaxation (Bourne 2002; Dobraszczyk and Morgenstern 2003).

Viscoelasticity is a very good tool for understanding problems in the food industry, therefore it is important to know the meaning of the linear and non-linear range which will depend upon the applied deformation. When a product is tested in the linear range, its functions will not depend on the magnitude of stress, strain or strain rate. If linear, an applied stress will produce a proportional strain response. However, very small deformations (sometimes up to 1%) are necessary to be in the linear range. As most of the products in the food industry undergo large deformations, such as mastication, in hot press wheat flour tortilla production, the non-linear range is the most important to be studied (Steffe 1996).

Stress relaxation

This is a method in which an instantaneous strain is applied and the stress required to maintain the deformation is observed as a function of time. An ideal elastic material would show no relaxation while the ideal viscous material would relax instantaneously. Viscoelastic materials such as wheat flour dough would relax gradually with the end point (equilibrium stress) depending on the molecular structure of the material being tested (Steffe 1996).

Many models have been developed to analyze viscoelastic properties of foods. Among those, the Peleg equation and the modified Maxwell equation have been proven valid for many food products (Peleg 1979, Peleg and Norman 1983).

Peleg (1979) developed a simple method for the mathematical presentation of relaxation curves. This method is not based on either a mechanistic assumption or a rheological model, therefore, it is equally applicable to materials that are in the linear or nonlinear range; small and large deformation may be treated by the same procedure.

Rodriguez-Sandoval et al (2008) used the stress relaxation technique to evaluate the textural characteristics of cassava dough. Srinivasan (1996) showed that the equilibrium modulus correlated significantly with subjective wheat flour dough evaluations. Suhendro (1997) used the arrheodictic Weichert model and discovered that fresh corn tortillas exhibited more viscous-like behavior with lower equilibrium modulus values while stale tortillas had solid-like behavior with higher equilibrium modulus values. Limanond (2000) and Bejosano et al (2005) evaluated stress relaxation tests for corn tortillas and wheat flour tortillas, respectively, using a seven-element Maxwell model to calculate initial and final stiffness and energy dissipation. It was a good technique to detected texture differences between the samples during storage to corn tortillas as well as to wheat flour tortillas.

Besides the stress relaxation technique, other fundamental tests are often used in the food rheology field, such as dynamic oscillatory method and creep tests (Schober et al 2002). They used wet gluten from spelt cultivars in their research to prove that their baking quality is determined by gluten properties.

Along with dough rheology, gluten has been investigated as the main factor providing dough with unique viscoelastic behavior and a simpler structure. In bread studies, dynamic measurements of gluten have been performed by many researchers (Schober et al 2002; Dreese et al 1988; Dreese and Hoseney 1990; Attenburrow et al 1990) as well as uniaxial extension measurements on gluten (Rinde et al 1970).

Information about the structure of both dough and gluten is obtained using mechanical tests involving small deformations, such as dynamic rheological tests. However, those measurements are not practical because during the baking process there are large deformations (Kokelaar et al 1995). They concluded that besides using a combination of different rheological tests, evaluating both dough and gluten rheology is important to provide enough information to improve the final product quality.

MULTI-VARIABLE APPROACHES

Faergestad et al (2000) used 17 samples to study the relationship between rheological parameters and different kinds of bread. They included one pan loaf test, and two hearth bread tests with different mixing procedures. Using Partial Least Square analysis (PLS), they observed that the volume and the form ratio were affected differently by flour quality. A PLS model was used to explain breadmaking characteristics of 20 Norwegian flours with extensional tests and gluten composition (Tronsmo et al 2003).

Dowell et al (2008) studied the relationship between bread quality with 49 hard red spring and 48 hard red winter grain, flour and dough quality properties. Regression models were developed using SAS and Mallows Cp statistics. The best fit models for loaf volume, bake mix time and water absorption had r^2 values of 0.78-0.93. Millar (2003) and Lee et al (2006) predicted bread loaf volume using stepwise regression. They got an r^2 of 0.39 and 0.70, respectively.

CHAPTER III

DETERMINATION OF POSSIBLE TORTILLA QUALITY PREDICTOR (S)

MATERIALS AND METHODS

Raw materials

Sixteen wheat flours from the 2007 Wheat Quality Council (WQC) were used in the following tests. Physico-chemical data of the grains and flours, farinograph and mixograph contents of the wheat flours were provided by the WQC.

Evaluation of flours

The flours were further analyzed for the following:

Sedimentation test

This test was done according to SDSU Winter Wheat Protocol. The measured gel height is believed to correlate with farinograph and mixograph data. One gram of flour was weighed into ten test-tubes per batch. Four milliliters of distilled water was added to each tube and samples were mixed using a vortex. The tubes were rested for 4 min and 54 sec. After that, they were mixed for 4 more min and rested again for 4 min and 54 sec. Then, 12 mL of the reagent (SDS-lactic acid) was added. Immediately, the tubes were covered with parafilm and subsequently with foam pad. The tubes were inverted ten times and rested for 15 min. The sedimentation height was measured using a millimeter ruler.

True density

This was measured using a multi-pycnometer (MVP-1, Quantachrome Corp., Syosset, NY).

Dough and tortilla preparation

Dough and tortillas were prepared by the method described by Alviola et al (2008) with some modifications (Fig.1). The following ingredients were used: 500 g wheat flour, 30 g shortening (Sysco Corp., Houston, TX), 7.5 g salt (Morton International, Inc., Chicago, IL), 3 g sodium bicarbonate (Arm and Hammer, Church and Dwight Company, Inc, Princeton, NJ), 2.9 g sodium aluminum sulfate (Budenheim USA, Inc, Plainview, NY), 2.5 g sodium steroyl lactylate (Caravan Ingredients, Lenexa, KS), 2 g sodium propionate (Niacet Corp., Niagara Falls, NY), 2 g potassium sorbate (B.C.Williams, Dallas, TX), 1.65 g encapsulated fumaric acid (Balchem Corp., New Hampton, NY), 0.015 g cysteine (Fleishmann’s yeast, Inc., Burr Ridge, IL) and distilled water (amount varied according to the water absorption of each wheat flour).

After mixing, the dough was proofed for 5 min (32-35^{o}C, 70-75% RH, Model 57638, National Manufacturing Co., Lincoln, NE) and subjectively evaluated.

Then, the dough was pressed into a stainless steel plate, divided and rounded into 18 dough balls (Dutchess Tool Co.,Beacon, NY). After resting, dough balls were evaluated for rheological properties using the texture analyzer (model TA.XT2i, Texture Technology Corp., Scarsdale, NY).

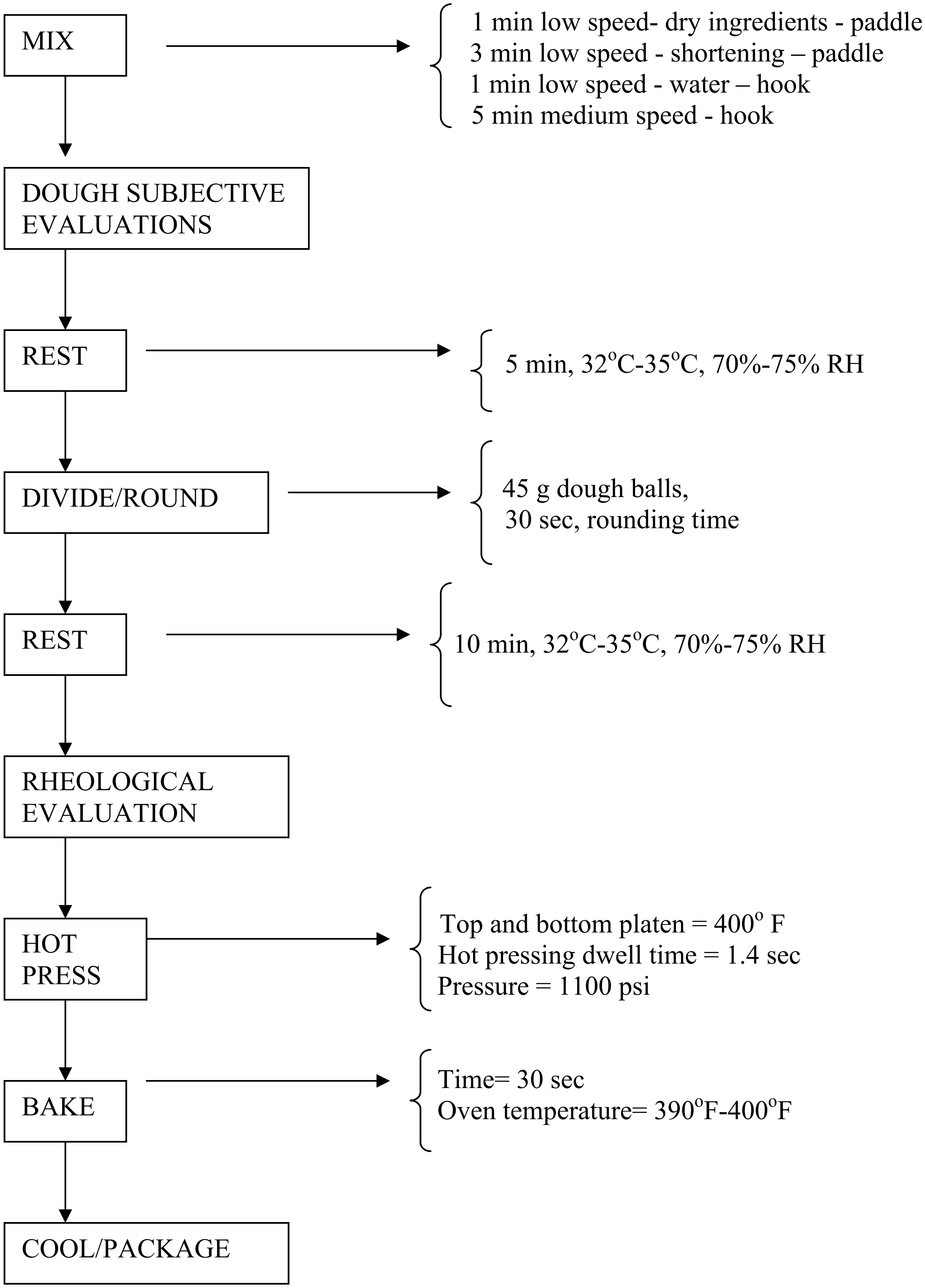


Fig.1. Production scheme for hot-press wheat flour tortilla.

Tortillas were produced by the hot-press procedure. Dough balls were pressed and baked in a three-tier gas fired-oven (model 0P01004-02, Lawrence Equipment, El Monte, CA). The tortillas were cooled on a three-tier conveyor (Model 3106-INF, Superior Food Machinery Inc., Pico Rivera, CA) and placed on a sanitized table. After that, tortillas were packed in polyethylene bags and stored at ambient temperature (22^{o}C).

Subjective evaluations of dough properties

Immediately after mixing, the doughs were evaluated for smoothness, softness, extensibility and force to extend. Each property was graded on a subjective scale from 1 to 5 (Table I).

Objective evaluation of dough properties with a TA.XT2i texture analyzer

The rheological properties of wheat dough were analyzed using a texture analyzer. The methods were: Texture profile analysis (TPA), stress relaxation and dough/gluten extensibility.

Texture profile analysis

A dough ball (average height = 2.1 cm, average diameter = 5.2 cm, average weight = 45.0 g) was placed on a flat stationary aluminum platform (Fig 2) and compressed with an aluminum cylindrical probe (10 cm in diameter).

The test speed was 10 mm/s. The dough ball was compressed to 70% of its original height and had a surface area of 2000 mm^2. Hardness, cohesiveness, adhesiveness and springiness were measured.

TABLE I
Description of scale used for subjective evaluation of wheat flour doughs

Score Description	Smoothness [a]	Softness [b]	Extensibility [c]	Force to Extend [d]
1	Very smooth	Very soft	Breaks immediately	Less force
2	Smooth	Soft	Some extension	Slight force
3	Slightly rough	Slightly hard	Extension	Some force
4	Rough	Hard	More extension	More force
5	Very rough	Very hard	Extends readily	Extreme force

a- Refers to the appearance and texture of the dough surface; b- Refers to the viscosity or firmness of the dough when compressed with the fingers; c- Refers to the length the dough extends when pulled apart; d- Refers to the elasticity of the dough when pulled apart.

Fig. 2. Set up for the objective Texture profile analysis (TPA) test.

The setup and method used for TPA is given in Table II and the parameters measured are defined in Table III. A typical texture profile curve for wheat flour dough is given in Appendix, Fig.A1.

Stress relaxation method

An instantaneous strain was applied to the dough ball (average height = 2.1 cm, average diameter = 5.2 cm, average weight = 45 g). The test speed was 10 mm/s, force of 80 N was used and the holding time was 100 sec. The dough ball was placed on a flat stationary aluminum platform (Fig 3) and pressed by an aluminum probe (10 cm in diameter). The complete setup and parameter descriptions are given in Table IV and V. A typical stress relaxation graph is presented in Appendix, Fig. A2.

The test was conducted in the non-linear viscoelastic region (75%). According to Srinivasan (1996), the linear region for tortilla dough is between 2% and 6% strain. The procedures according to Peleg (1979), Peleg and Normand (1983) were followed. The equation from the Peleg and Normand's model is given below.

$$\frac{F(0).t}{F(0)-F(t)} = \mathrm{k1} + \mathrm{k2.t}$$

From this equation, k1 (initial rate of relaxation) and k2 (extent of relaxation) were calculated by linear regression of the data generated (Fig. 4).

Dough and gluten extensibility test

<u>Dough</u>

The test according to Smewing (1995), which uses the Kieffer dough and gluten extensibility rig (Fig 5), was followed with modifications.

TABLE II
TPA setup and method for the TA.XT2i Texture Analyzer

Parameter	Settings	
Test mode/options	TPA	
Parameters	Pre test speed	5 mm/s
	Test speed	10 mm/s
	Post test speed	5 mm/s
	Distance	70% strain
	Time	5 sec
	Data acquisition rate	200 pps
	Contact area	2000 mm^2
	Load cell	25 kg
Trigger	Type	Auto
	Force	0.05 N

TABLE III
Parameters recorded by TPA

Parameter	Units	Description
Hardness	N	Force necessary to attain certain deformation in the sample
Cohesiveness	No units	Ratio of the positive area during the second compression to that during the first compression
Adhesiveness	Nmm	Work required to overcome the adhesion between the probe and sample
Springiness	mm	Distance from the beginning of the second compression to the second peak. Elasticity of the material

Fig. 3. Set up of the objective stress relaxation test

TABLE IV
Stress Relaxation setup and method for the TA.XT2i Texture Analyzer

Parameter	**Settings**	
Test mode	HLDD (Force relaxation)	
Parameters	Pre test speed	5 mm/s
	Test speed	10 mm/s
	Post test speed	5 mm/s
	Force	80 N
	Time	100 sec
	Data acquisition rate	100 pps
	Load cell	25 kg
Trigger	Type	Auto
	Force	0.05 N

TABLE V
Parameters measured by stress relaxation of wheat flour doughs

Parameter	**Units**	**Description**
Equilibrium Modulus	Pa	Residual stress left in the sample after reaching equilibrium
Relaxation time	sec	The time it takes for the maximum force to decay to 36.8% of its value.
k1	sec	Initial rate of relaxation
k2	No units	Extent of relaxation

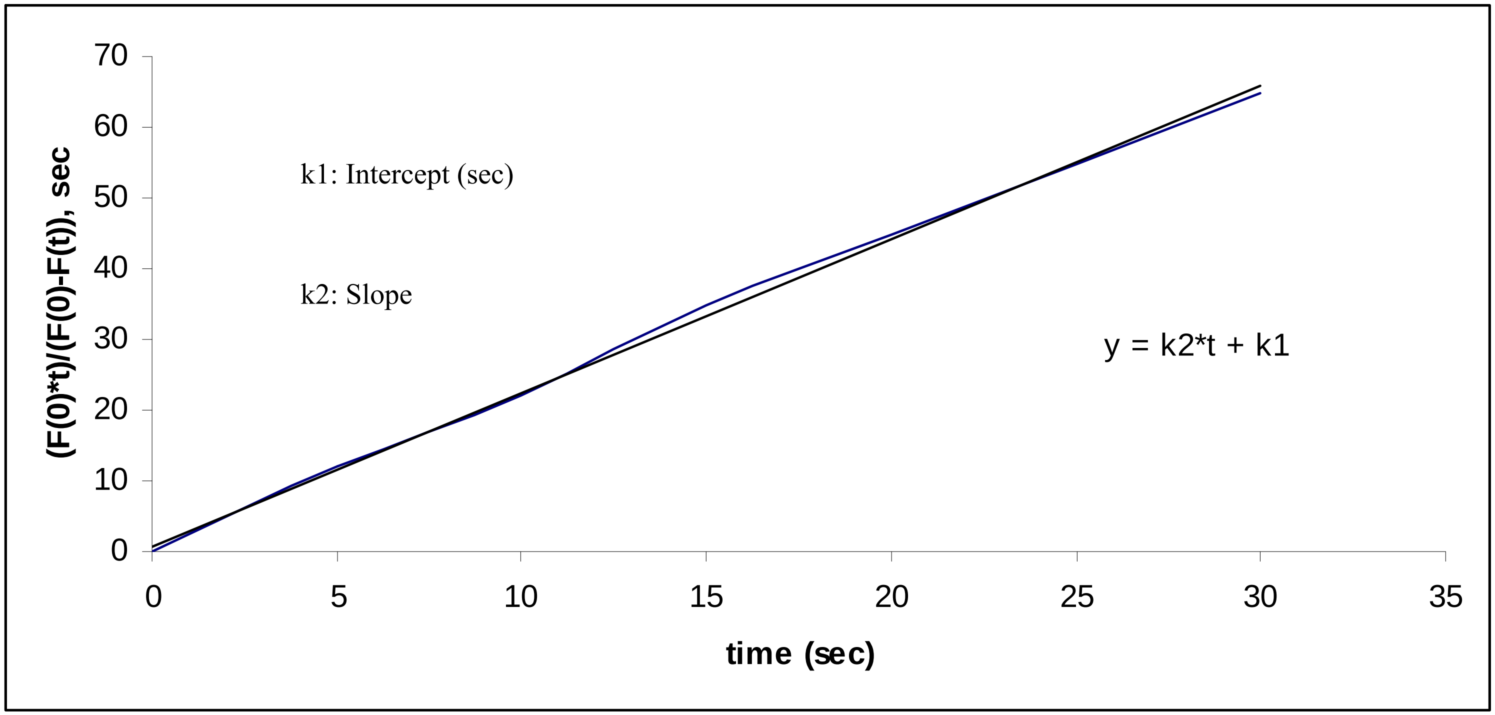


Fig. 4. Stress relaxation data after conversion to linear form to calculate k1 and k2.

Fig. 5. Testing set up of the objective extensibility test (Smewing 1995)

After resting the dough balls for 10 min in the proofing chamber, 20 g of one dough ball was weighed and rolled into a cylindrical shape with as little manipulation as possible.

The dough press with a grooved base and a top form was used to prepare the samples. Paraffin oil was placed along the grooved base to aid the removal of the dough strips, avoiding sample adhesion.

The dough sample was placed on the grooved base with its length perpendicular to the groove direction. The top form was then placed on the grooved base. The dough press was placed in the clamp and screwed down. Excess dough extruding from the sides was removed using a spatula. This process cut the sample into strips. The dough clamp was placed into a plastic bag and left to relax for 40 min at room temperature. After that, the plastic bag was opened, and the clamp was released and the dough press was removed. Dough strips were removed for the test with a thin spatula. The dough strip was then placed across the grooved region of the sample plate.

The hook probe was lowered to the surface of the spring loaded clamp. The lever of the spring loaded clamp was lowered and the sample plate was inserted into the rig. The handle was released slowly and the test was conducted. The hook probe extended the dough sample centrally until it ruptured. Texture analyzer settings for the extensibility test are given in Table VI and the definitions of the parameters measured are presented in Table VII. Typical graph for dough extensibility is given in Appendix, Fig.A3.

TABLE VI
Extensibility setup and method for the TA.XT2i Texture Analyzer

Parameter	Settings	
Test mode/options	Measure force in tension: return to start	
Parameters	Pre test speed	2 mm/s
	Test speed	3.3 mm/s
	Post test speed	10 mm/s
	Distance	105 mm
	Data acquisition rate	200 pps
	Load cell	5 kg
Trigger	Type	Auto
	Force	0.05 N

TABLE VII
Parameters measured in the extensibility test

Parameter	Units	Description
Resistance to extension	N	Force required to stretch a sample until it ruptures. Sample elasticity
Extensibility	mm	Distance to which the sample flows before rupturing

Gluten

For sample preparation, the AACC Method 38-10 (Hand Washing Method) was used to obtain gluten from dough (AACC International 2000). The extensibility test was done similarly to that of the dough following Smewing (1995). The only differences were: the gluten was placed on the grooved base with its length parallel to the groove direction and there was no need to add paraffin oil along the grooved base.

Objective evaluation of tortilla properties on a TA.XT2i texture analyzer

The two-dimensional extensibility test for tortillas (Fig. 6) was followed according to Alviola et al (2008) and Bejosano et al (2005). Firmness and extensibility were tested using the TA-108 fixture. The metal template from the aluminum platform was used to punch four holes to hold the tortilla in place. The tortilla was extended and ruptured using an acrylic probe of 7/16-in. diameter with a flat edge to minimize cutting or tearing of the tortilla.

Texture analyses were done over 12 days of storage using a TA.XT2i Texture Analyzer. The tortillas were evaluated objectively on the day of processing (day 0), and 4, 8 and 12 days after processing.

The conditions for this test are mentioned in Table VIII. The parameters measured in this test are defined Table IX. Typical graph for the two-dimensional extensibility test is given in Appendix, Fig.A4.

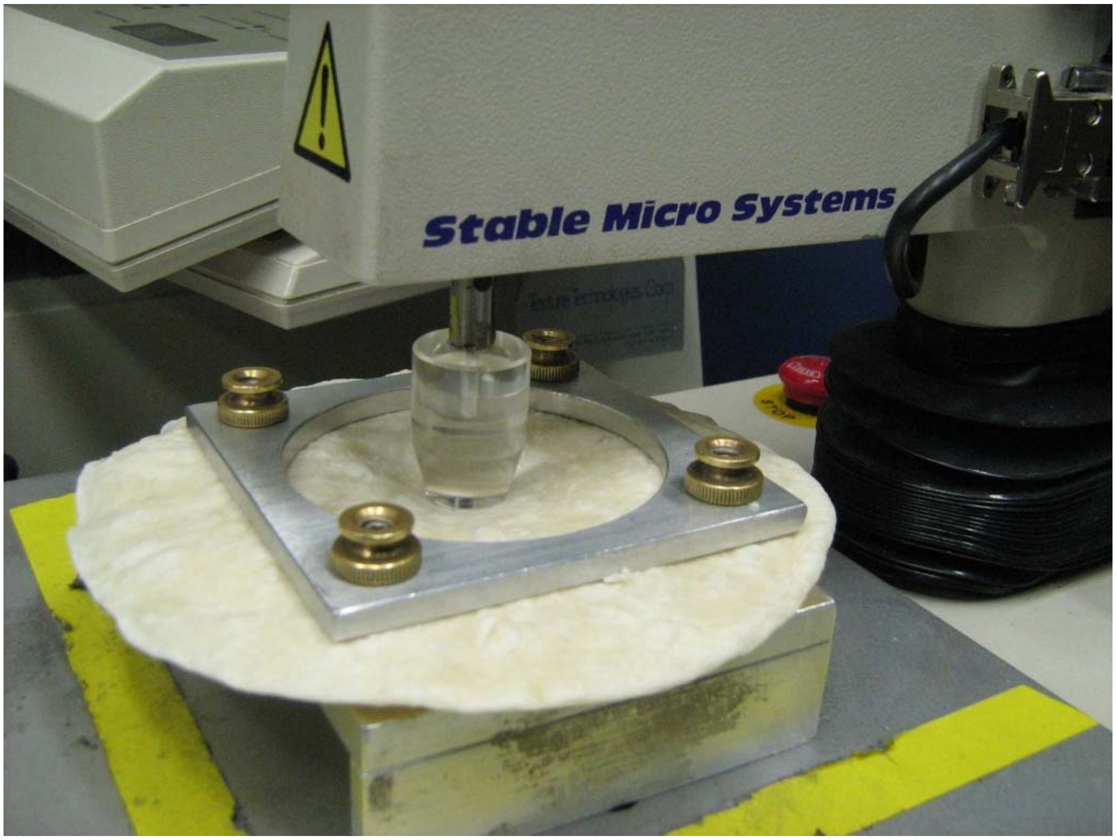


Fig. 6: Set up of the objective two-dimensional extensibility test

TABLE VIII
Two-dimensional extensibility setup and method for the TA.XT2i Texture Analyzer

Parameter	**Settings**	
Test mode/options	Measure force in compression: return to start	
Parameters	Pre test speed	5 mm/s
	Test speed	1 mm/s
	Post test speed	5 mm/s
	Distance	30 mm
	Data acquisition rate	200 pps
	Load cell	5 kg or 25 kg
Trigger	Type	Auto
	Force	0.05 N

TABLE IX
Parameters measured in the two-dimensional extensibility test

Parameter	**Units**	**Description**
Deformation modulus	N/mm	Slope of the curve
Maximum force	N	Firmness, hardness of the sample
Work	Nmm	Measure of energy. Area under the curve until rupture
Rupture distance	mm	Measure of the sample extensibility

Evaluation of physical properties of tortillas

Ten tortillas from each batch, prepared on two different days, were randomly selected and measured for weight; thickness, using a caliper (Chicago brand 12" Electronic Digital Caliper, Chicago IL); diameter, measured from 2 points for each tortilla, and opacity after one day of storage. Opacity score varied from 0% (complete translucency) to 100% (complete opacity) (Alviola et al 2008). Likewise, two tortillas from each batch were randomly selected and measured for color using a chroma meter (model CR-300, Minolta Camera Co., Ltd., Chuo-Ku, Osaka, Japan). Values for L* (brightness or whiteness), a* (redness and greenness), and b* (yellowness and blueness) were determined. Moisture content was determined using Approved Method 44-15A (AACC International 2000).

The tortillas were also subjectively evaluated using the rollability technique, 4, 8 and 12 days after processing. A tortilla was wrapped and rolled around a 1 cm wooden dowel. Rollability score was rated from 1 (breaks immediately; cannot be rolled) to 5 (no cracks; very flexible). Tortillas were considered unacceptable when the rollability score was lower than 3 (Alviola et al 2008).

Tortilla quality indicators were divided into two groups: physical properties (diameter, opacity and specific volume) and rheological properties obtained from the two-dimensional extensibility test on day 0 (deformation modulus, work, maximum force and distance needed to rupture the tortilla). Simple correlations between tortilla quality variables and all independent variables (grain, flour and dough tests) were done. After that, prediction models were developed for each tortilla quality variable (dependent variable). Data from the 2008 Wheat Quality Council (WQC) evaluations were used to validate the best predictors for tortilla quality.

Statistical analysis

Pearson's correlation was performed to investigate the relationships among wheat grain, flour characteristics and dough/gluten rheological tests with tortilla quality variables. Analysis of variance (ANOVA) using a completely randomized design was evaluated. To investigate differences between means Tukey's test was used in a confidence level of 95%. Tukey's Honest Significant Difference (HSD) was used for treatment comparisons. Stepwise multiple regression was performed to develop prediction models using wheat/flour characteristics and dough/gluten rheological properties as independent variables. A significance level of entry of 0.05 and a significance level of removal of 0.10 were used. The results of the prediction were evaluated by the coefficient of determination (r^2) and root mean square of error (RMSE). Tortillas were prepared in two different days. Physico-chemical tests were analyzed as mentioned previously and for the rheological analyses, two samples were analyzed per test. Flour and dough tests were also done on two different days, and three samples were analyzed per day. SPSS v14.0 for Windows (SPSS Inc.) was used for all the statistical tests.

RESULTS AND DISCUSSION

Characteristics of wheat grains and flour

The single kernel hardness of 16 wheats ranged from 53 to 80 (Table X). Kernel weight and diameter ranged from 29.2 to 38.5 mg and from 2.11 to 2.63 mm, respectively.

The wheat flours tested had an average protein content of 12%, varying from 10.92 to 13.35% (14% mb). This is above the regular protein content range used to manufacture tortillas (9.5% to 11.5%) (Waniska 1999). Particle size ranged from 19 to 24 microns. Gluten index ranged from 80.6 to 99.2 while wet gluten and dry gluten varied from 25.9 to 39.2% and from 9.5 to 14.3%, respectively (Table X). Dry gluten and wet gluten were highly correlated with protein at $r=0.88$ and $r=0.64$ ($P<0.01$), respectively.

Flour dough strength, estimated from farinograph and mixograph varied widely. Water absorption, development time, stability, breakdown time and tolerance index determined by a farinograph, ranged from 58.8-70.1%, 6.0-26.3 min, 10.7-31.6 min, 9.4-34.2 min and 0-30 BU, respectively (Table X).

Mix-time and mix-tolerance data determined by a mixograph ranged from 2.5 to 6 min and 1-6, respectively (Table X). Mixograms from these 16 flours are presented in Appendix, Fig. C1.

TABLE X
Wheat grain and flour properties (WQC, 2007)

Variables	FLOURS															
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Gain data																
Hardness (single kernel)	64	70	53	66	55	77	80	65	75	80	70	57	68	72	69	56
Single kernel weight (mg)	30.5	32.4	29.5	29.2	32.4	33.5	33.6	32	38.5	31.8	29.2	31.4	33.9	33.1	32.9	35.5
Single kernel diameter (mm)	2.22	2.34	2.11	2.13	2.32	2.55	2.55	2.4	2.63	2.34	2.22	2.16	2.41	2.27	2.43	2.41
Flour data																
Moisture (%)	10.56	10.65	10.93	10.92	11.44	11.29	11.41	12.41	12.47	12.05	11.40	12.27	11.7	12.06	12.86	12.98
Protein (14% mb)	13.23	13.35	13.25	11.91	11.03	12.4	11.61	11.73	10.92	12.13	12.3	11.94	12.39	11.12	11.03	11.72
Particle size (microns)	24	22.5	19.8	19.8	19	23.3	23.8	20.5	23	20.3	22.5	21.8	21.5	22	19.3	19
L*	92.45	92.45	92.93	92.27	92.33	91.48	91.51	92.02	92.28	92.07	92.49	92.51	92.21	92.13	92.53	92.74
a*	-1.57	-1.97	-1.77	-1.53	-1.47	-1.41	-1.42	-1.59	-1.39	-1.58	-1.4	-1.83	-1.78	-2.07	-1.82	-1.82
b*	9.57	10.45	9.58	9.11	8.53	9.07	9.36	9.94	9.01	9.71	8.93	10.35	10.81	11.7	10.18	10
Gluten Index	95.4	99.1	96.7	86.7	98.8	89.5	95.7	97.6	97.4	99.2	80.6	94.2	80.8	93	94.3	97.1
Wet gluten %	39.2	34.4	36.8	34.5	25.9	35.8	33.7	33	30.4	31.6	27.3	34.2	37.3	32.1	31.7	32.9
Dry gluten %	14.3	12.7	12.9	11.8	9.5	12.2	11.9	11.6	10.7	11.7	12.4	12.1	12.6	11	11	11.5
Farinograph data																
Water absorption (%)	64.2	70.1	65.1	62	58.8	65.5	65.1	62.3	65.5	63	63.7	62.2	63.2	64.1	61.9	60.5
Develop. time (min)	11.5	26.3	11	5.2	6.5	6	6.3	6.2	6.1	20.2	6.2	8.5	9	6.2	7.2	10
Stability (min)	24.6	28.7	31.4	10.7	18.5	11.9	14.9	14.9	19.1	31.6	13.5	20.2	17.7	14	13.3	19.1
Breakdown time (min)	27.5	34.1	34	9.4	20.1	10.2	12.8	12.5	12.6	34.2	14.2	22	19.6	14.5	12.7	21.6
Tolerance Index (BU)	12	0	9	30	13	31	23	20	21	0	21	15	18	18	27	11
Mixograph data																
Mix-time (min)	3.63	6	4.25	3	4.13	3	3.38	3.38	4.25	5.88	2.5	3.25	3	3	3	4
Mix tolerance	2	6	4	2	3	2	3	2	3	6	1	2	2	2	2	4

There were no significant differences ($P > 0.05$) among the 16 wheat flours in sedimentation height and true density data (Appendix, Table C1).

The sedimentation height of a weaker, commercial refined malted wheat flour (ADM Milling Co., Overland Park, KS), used as an extra flour for control was 8.92 cm ± 0.59 cm. This value was lower ($P < 0.05$) than those from the 16 wheat flours which are considered strong flours. This result confirms the hypothesis that the lower the sedimentation height, the weaker the wheat flour. However, when flours have relatively similar strength, this technique does not differentiate them.

Subjective evaluation of dough properties

The optimum water absorption used to make machineable tortilla doughs was 10% less than the farinograph water absorption (listed in Table X).

All 16 wheat dough had the same smoothness score ($P > 0.05$) with an average score of 1.6 (very smooth to smooth) (Appendix, Table C2). There were differences in softness ($P \leq 0.05$). The softest wheat dough had a score of 1.0 (very soft) and the least soft one had a score of 2.5 (soft to slightly hard). There were also significant differences ($P \leq 0.05$) in extensibility and force to extend. Their scores varied from 2.5 (some extension to extension) to 4.0 (more extension) and from 2.3 (slight force to some force) to 4.0 (more force), respectively.

Dough and gluten objective methods of evaluation

A texture analyzer (model TA.XT2i, Texture Technology Corp., Scarsdale, NY) was used for all the objective tests.

Extensibility test

Dough resistance to extension: Resistance to extension was measured as the force required to pull the dough strip apart and there were differences among the 16 wheat flours ($P \leq 0.05$) (Table XI). It ranged from 0.29 to 0.54 N and showed low variability (CV = 3-8.5%).

Dough extensibility: Extensibility is the distance to which the dough strip was extended before it ruptures. There were also differences among the samples ($P \leq 0.05$). The range was from 39.92 to 70.9 mm and the variability was also low (CV= 3.3-9.3%).

Gluten resistance to extension and extensibility: There were differences between the samples ($P \leq 0.05$) and the range was from 1.07 to 1.98 N for resistance to extension and from 33.99 to 62.0 mm for extensibility with variability a little higher than the ones from dough (CV= 4.3-14% and CV = 3.5-15.8%, respectively).

Comparisons between dough and gluten extensibility were made for each wheat sample. The trend observed is shown in Fig. 7. For all samples the resistance to extension was higher for gluten than for dough ($P \leq 0.05$) (Fig. 8). For the majority of the samples, dough was more extensible than gluten ($P \leq 0.05$) (Fig. 9). Kieffer et al (1998) obtained similar results. They also concluded that extensibility test of dough and gluten was a good estimator of bread loaf volume and the wheat flours with higher protein content gave a better result.

TABLE XI
Objective rheological tests: Dough and gluten extensibility test*

Flours	Dough tests: Resistance to extension (N)	Dough tests: Extensibility (mm)	Gluten tests: Resistance to extension (N)	Gluten tests: Extensibility (mm)
1	0.49f ± 0.024	56.91d,e ± 3.78	1.42b,c ± 0.13	49.52c,d ± 7.80
2	0.54g ± 0.022	44.74b ± 2.72	1.92f ± 0.25	47.46b-d ± 3.25
3	0.50f,g ± 0.041	58.60e ± 2.75	1.4b,c ± 0.081	59.35f,g ± 6.67
4	0.32a,b ± 0.023	60.39e ± 3.78	1.26a,b ± 0.054	60.62g ± 2.85
5	0.42e ± 0.020	56.90d,e ± 3.55	1.98f ± 0.15	50.76c-e ± 4.01
6	0.37c,d ± 0.021	62.30e,f ± 4.40	1.38b,c ± 0.083	58.33e-g ± 4.02
7	0.33a,b ± 0.028	70.50g ± 6.55	1.07a ± 0.15	57.77e-g ± 9.71
8	0.50f,g ± 0.040	52.10c,d ± 2.83	1.47b-d ± 0.064	54.74d-g ± 7.83
9	0.34b,c ± 0.015	66.78f,g ± 2.18	1.56c-e ± 0.11	41.57b ± 3.36
10	0.52f,g ± 0.039	50.68c ± 4.13	1.65d-e ± 0.12	33.99a ± 2.91
11	0.29a ± 0.010	66.36f,g ± 3.58	1.45b-d ± 0.066	42.26b ± 2.73
12	0.38d,e ± 0.021	57.61e ± 4.73	1.43b,c ± 0.10	51.18c-e ± 5.22
13	0.31a,b ± 0.014	70.90g ± 5.32	1.57c-e ± 0.085	46.73b,c ± 4.32
14	0.32a,b ± 0.022	65.58f,g ± 3.02	1.26a,b ± 0.066	62.00g ± 2.14
15	0.30a,b ± 0.009	78.54h ± 3.65	1.3b ± 0.17	52.08c-f ± 4.32
16	0.51f,g ± 0.038	39.92a ± 3.11	1.69e ± 0.16	44.26b,c ± 1.87

*Means followed by the same letter in the same column are not significantly different ($P \leq 0.05$)

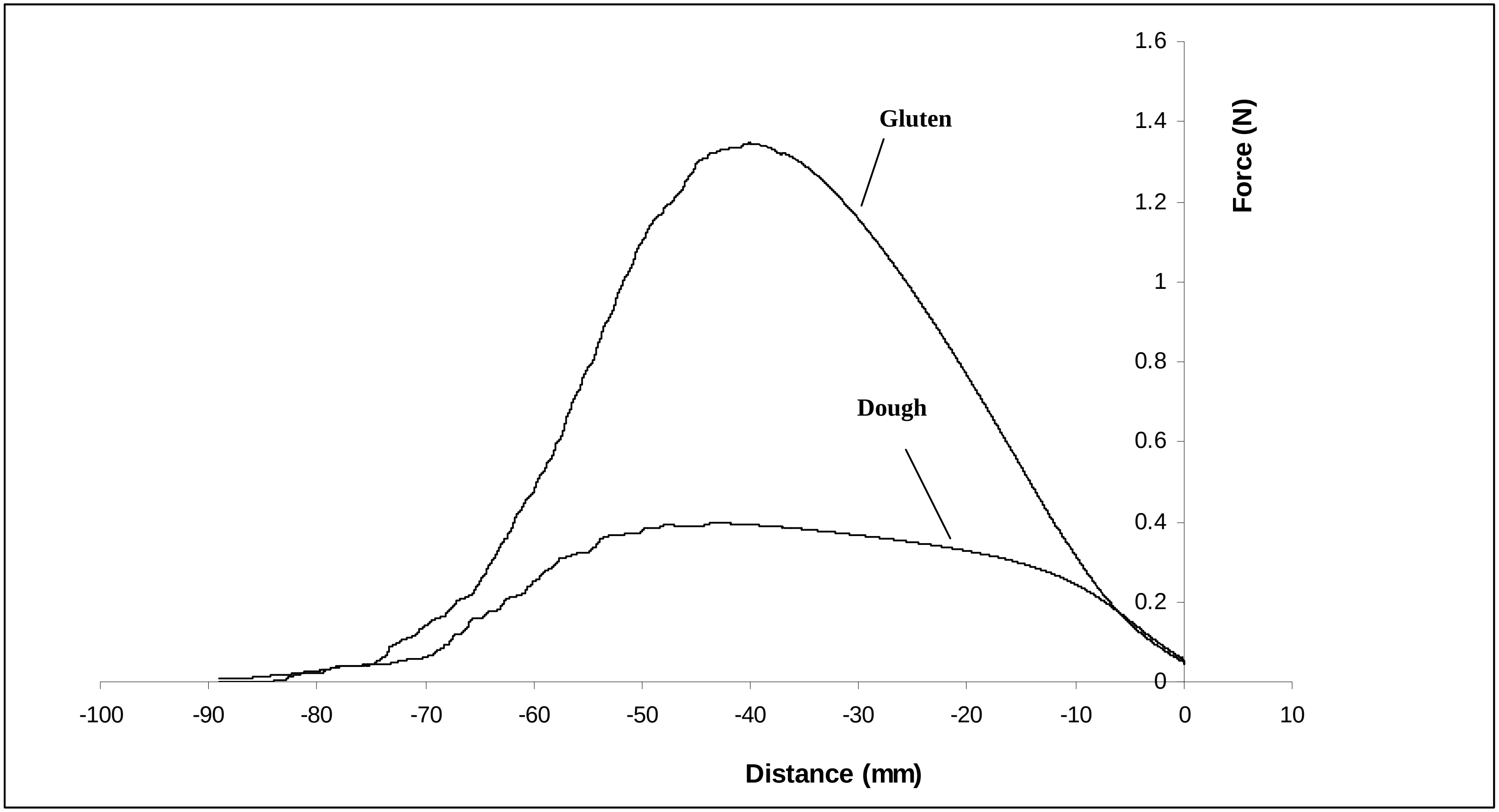


Fig. 7. Typical behavior observed of dough and gluten extensibility test

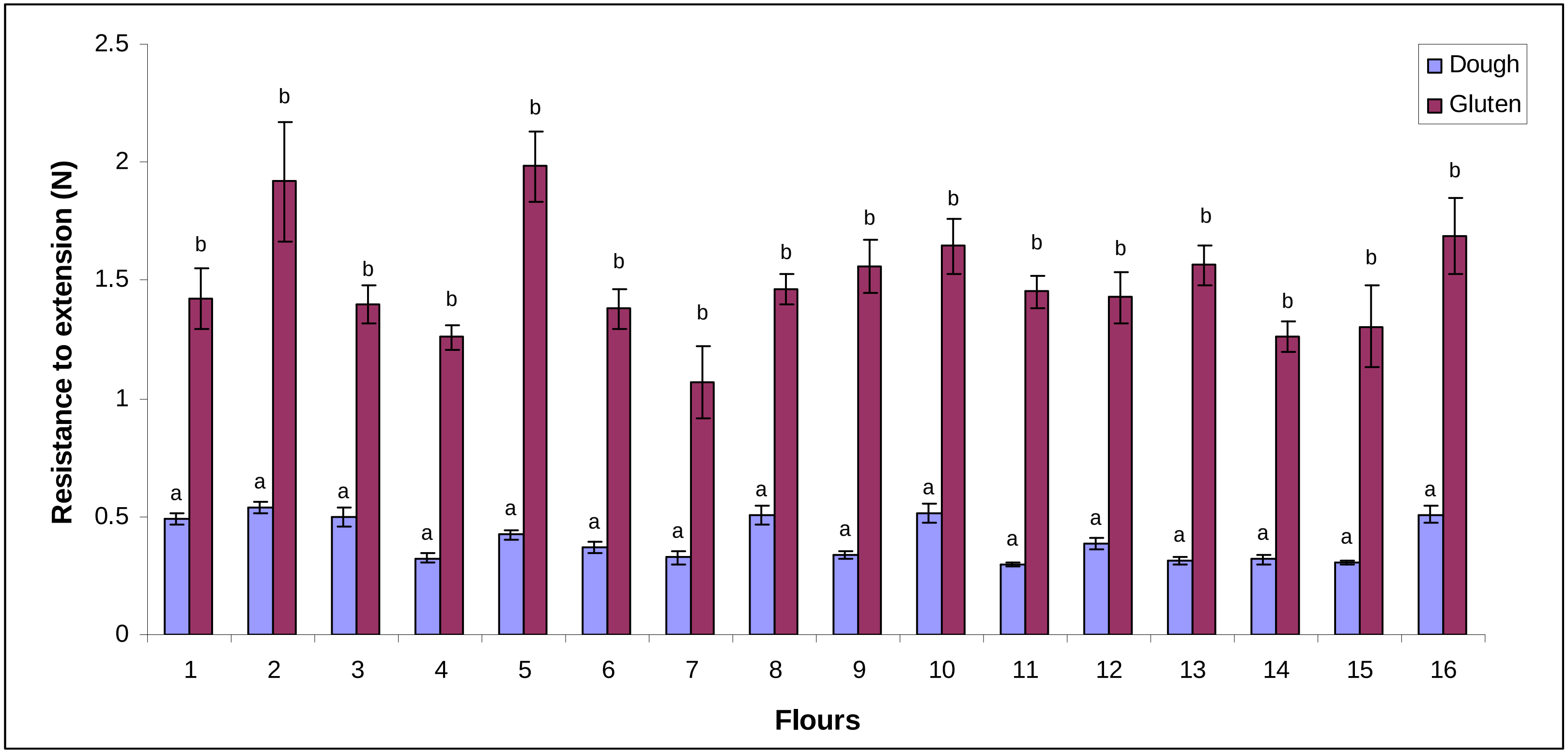


Fig. 8. Resistance to extension of dough and gluten from 16 wheat samples.

Values followed by the same letter for each flour are not significantly different (P≤ 0.05).

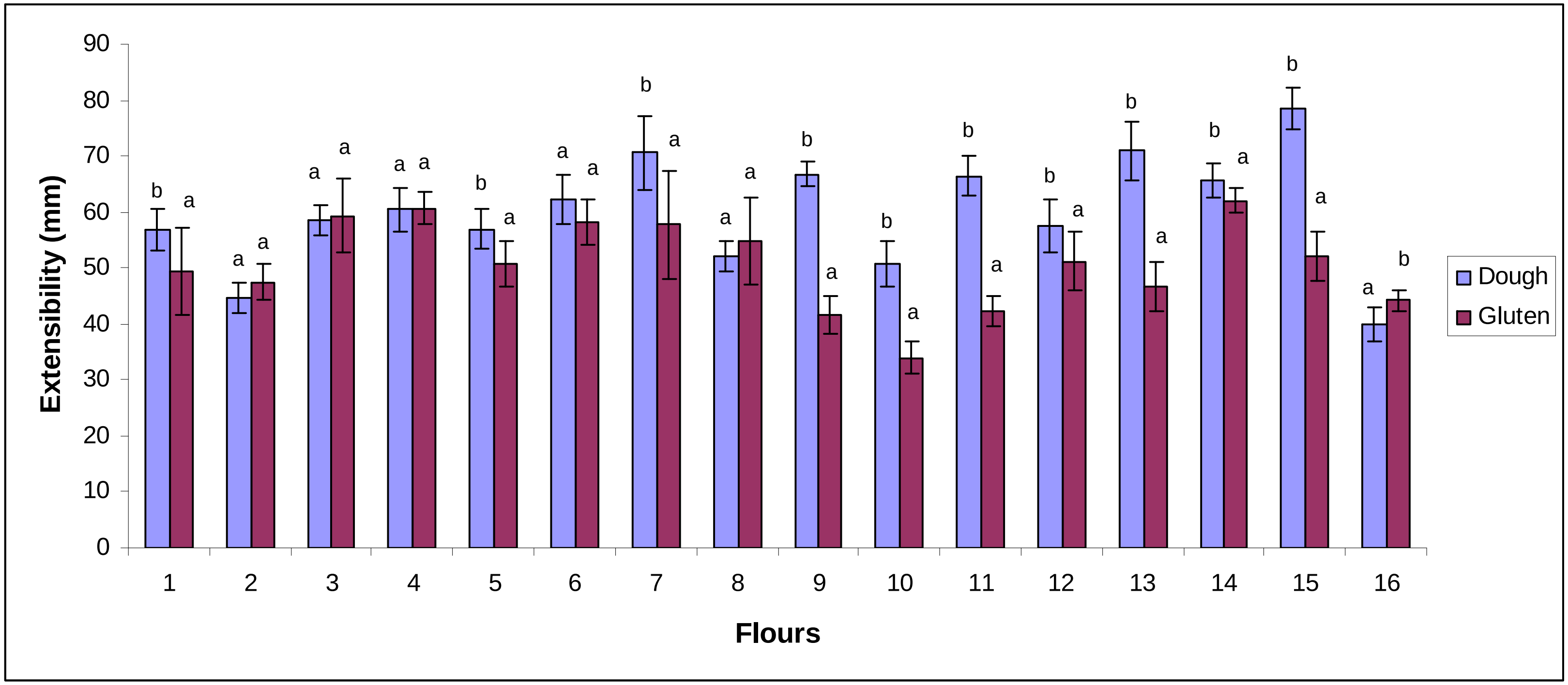


Fig. 9. Extensibility of dough and gluten from 16 wheat samples.

Values followed by the same letter for each flour are not significantly different (P≤ 0.05).

The differences between dough and gluten rheology in the extensibility test can be discussed in relation with their different compositions. Protein concentration increases when gluten is isolated, therefore forming more cross-links relative to the dough. This increases elasticity or resistance to extension and decreases extensibility of gluten. Starch and other components would dilute the protein, weakening the chemical bonds among them. The higher the protein concentration, the stronger the network and therefore the more stress that network can support (MacRitchie 1992).

On a moisture-free basis, wheat flour contains approximately 80% starch, 14% protein, 4-5% lipids, and 2% pentosans (Chung 1986). The interaction between starch and protein in wheat flour has been studied by Petrofsky and Hoseney (1995). They concluded that not only gluten, but starch properties determine dough rheological properties. The strength of this interaction can be responsible for baking differences.

Gluten composition gives some idea of how difficult it is to relate rheological properties like extensibility. Several researchers have proposed that extensibility is not related only to the total amount of gluten, but also its fractions. In general it is understood that glutenins contribute to dough elasticity and gliadins contribute to dough viscosity or extensibility (MacRitchie 1987, Janssen et al 1996, Gianibelli et al 2001). In a more detailed study Uthayakumaran et al (1999) observed that an increase in the glutenin to gliadin ratio with constant protein was associated with decreased extensibility.

TPA test

There were differences ($P \leq 0.05$) among the 16 wheat doughs in hardness, cohesiveness, adhesiveness and springiness (Table XII). They varied from 116.4 to 179.6 N for hardness (CV = 3.3-14.4%), 0.40 to 0.49 for cohesiveness (CV = 2.9-13%), 13.1 to 30.8 Nmm for adhesiveness (CV = 11.6-63%) and from 3.0 to 4.2 mm for springiness (CV = 2.2 - 20.5%). Adhesiveness and springiness presented high variability.

Geometry and weight of the sample was found to be important in this study. A major problem encountered was the temperature and relative humidity of the room in which the experiment was conducted which affected the surface of the dough. Temperature and relative humidity were kept as constant as possible for all tests; however, variations may have occurred.

Stress relaxation test

This test, like the other objective tests, showed differences ($P \leq 0.05$) among the dough samples (Table XIII). Equilibrium modulus or equilibrium stress varied from 28.6 to 40.9 Pa (CV = 1.1-6.5%). Relaxation time ranged from 1.54 to 1.81 sec (CV = 2.2-13.4%).

In theory, relaxation time and equilibrium modulus have the same behavior. The higher the value the more elastic (more solid like) the sample is. As an example, a weak gluten network enables the dough to relax easily, and have a lower equilibrium modulus and a shorter relaxation time.

TABLE XII
Objective rheological tests: *Texture profile analysis (TPA)* test*

Flours	**Variables**			
	Hardness (N)	**Cohesiveness**	**Adhesiveness (Nmm)**	**Springiness (mm)**
1	116.4a ± 16.82	0.47a,b ± 0.022	13.1a ± 2.99	4.2f ± 0.206
2	121.3a-c ± 10.08	0.48a,b ± 0.014	17.0a,b ± 3.94	4.0d-f ±0.219
3	119.6a,b ± 6.94	0.49b ± 0.016	14.2a ± 1.65	4.1e,f ± 0.175
4	144.6e ± 17.68	0.47a,b ± 0.016	22.7a,b ± 4.72	3.5a-e ± 0.199
5	179.6f ± 10.33	0.48a,b ± 0.025	19.3a,b ± 5.24	3.4a-d ± 0.173
6	140.8d,e ± 13.45	0.4a ± 0.020	22.6a,b ± 7.91	3.0a ± 0.198
7	119.3a,b ± 7.84	0.43a,b ± 0.022	18.7a,b ± 9.08	3.6a-e ± 0.146
8	137.6c-e ± 12.71	0.47a,b ± 0.057	18.1a,b ± 3.78	3.6a-f ± 0.253
9	132.4a-e ± 14.35	0.47a,b ± 0.061	30.8b ± 11.26	3.8b-f ± 0.083
10	124.6a-d ± 7.70	0.47a,b ± 0.033	17.0a,b ± 5.78	4.0d-f ± 0.146
11	130.4a-e ± 11.10	0.45a,b ± 0.048	22.7a,b ± 11.24	3.3a-c ± 0.373
12	142.4e ± 9.94	0.44a,b ± 0.049	17.6a,b ± 10.22	3.3a-c ± 0.397
13	127.3a-e ± 4.17	0.46a,b ± 0.030	25.8a,b ± 9.27	3.2a,b ± 0.208
14	127.3a-e ± 8.26	0.43a,b ± 0.071	20.3a,b ± 12.74	3.2a,b± 0.664
15	134.9b-e ± 8.14	0.47a,b ± 0.024	19.3a,b ± 5.63	3.3a-c ± 0.239
16	132.6a-e ± 10.35	0.48a,b ± 0.029	18.5a,b ± 10.44	3.9c-f ± 0.508

*Means followed by the same letter in the same column are not significantly different ($P \leq 0.05$)

TABLE XIII
Objective rheological tests: Stress relaxation test*

Flours	**Variables**			
	Equilibrium modulus (Pa)	**Relaxation time (sec)**	**k1 (sec)**	**k2**
1	36.9e,f ± 0.83	1.81d ± 0.10	1.1b-d ± 0.06	1.1d,e ± 0.003
2	39.3f,g ± 1.25	1.73a-d ± 0.05	1.11b-d ± 0.05	1.11e,f ± 0.003
3	38.8e-g ± 2.03	1.81d ± 0.04	1.2c,d ± 0.12	1.113f ± 0.003
4	31.3a-c ± 0.74	1.61a-c ± 0.07	1.01a-c ± 0.07	1.09b,c ± 0.001
5	36.4d-f ± 1.12	1.57a,b ± 0.06	1.0a,b ± 0.03	1.1d,e ± 0.002
6	31.8b,c ± 1.16	1.72a-d ± 0.08	0.88a ± 0.02	1.09c,d ± 0.005
7	31.1a-c ± 1.56	1.75b-d ± 0.05	1.06b-d ± 0.12	1.08a,b ± 0.004
8	35.9d,e ± 1.76	1.71a-d ± 0.07	1.07b-d ± 0.08	1.1c,d ± 0.005
9	33.8c,d ± 0.37	1.69a-d ± 0.05	1.13b-d ± 0.06	1.09b,c ± 0.003
10	40.9g ± 0.96	1.71a-d ± 0.06	1.24d ± 0.06	1.11e,f ± 0.004
11	30.7a,b ± 0.84	1.71a-d ± 0.23	0.99a,b ± 0.12	1.08a,b ± 0.002
12	29.3a,b ± 1.21	1.63a-d ± 0.06	0.98a,b ± 0.08	1.08a,b ± 0.005
13	29.9a,b ± 1.33	1.54a ± 0.14	1.01a,b ± 0.07	1.08a,b ± 0.005
14	28.6a ± 1.61	1.64a-d ± 0.06	1.03a-c ± 0.04	1.07a ± 0.007
15	29.3a,b ± 0.71	1.61a-c ± 0.09	0.97a,b ± 0.06	1.08a ± 0.004
16	37.3e,f ± 2.43	1.78c,d ± 0.06	1.1b-d ± 0.12	1.1d,e ± 0.008

*Means followed by the same letter in the same column are not significantly different ($P \leq 0.05$)

The constants from Peleg and Normand equation, k1 and k2, varied from 0.88 to 1.24 sec (CV = 2.3 - 12.1%) and from 1.07 to 1.11 (CV = 0.09-0.7%), respectively. Despite low variability, these constants did not differentiate the samples.

Those physico-chemical characteristics of wheat kernels and wheat flour, and dough/gluten rheological properties were included into models to predict tortilla quality as independent variables.

Tortilla physical tests

Diameter, thickness, weight, specific volume, moisture, color (L*, a* and b*), and opacity were determined (Table XIV).

There were differences ($P \leq 0.05$) among the samples in diameter, thickness, moisture, L*, a*, b* and opacity and their ranges were 150.8 – 173.45 mm, 2.54 – 3.05 mm, 30.44 – 35.10%, 81.97 – 85.43, -1.01 – 0.07, 16.79 – 21.10 and 88 – 92.3, respectively. No significant difference ($P > 0.05$) was observed in weight (average of 40.9 g) and specific volume (average of 1.44 cm^3/g) (Table XIV).

According to Pascut et al (2004), good quality wheat flour tortillas usually have large diameters (17-18 cm), are opaque (90-100%), have light color (high L* values) and are well puffed (related to specific volume). Most tortillas had a diameter smaller than 17 cm because the 16 wheat flours were relatively strong. Whiter tortillas are more acceptable (Waniska et al 2004), and the results indicated higher opacity scores and L* values, indicating whiter tortillas. Specific volume gives an idea of puffiness.

TABLE XIV
Tortilla physical properties

Flours	Diameter (mm)	Thickness (mm)	Weight (g)	Specific volume (cm^3/g)	Moisture (%)	L*	a*	b*	Opacity (%)	Rating**
1	159.9 (2.3)[1]	2.67 (0.1)	42.19 (2.3)	1.27 (0.08)	32.84 (1.4)	83.06 (1.0)	-0.49 (0.3)	18.18 (0.9)	89 (2.0)	Fair
2	150.8 (4.3)	3.05 (0.09)	41.54 (0.51)	1.31 (0.05)	35.10 (0.9)	82.62 (0.9)	-0.88 (0.3)	20.44 (0.95)	89.5 (1.5)	Fair
3	158.45 (4.6)	2.69 (0.2)	40.26 (0.33)	1.32 (0.22)	33.64 (1.3)	84.42 (1.4)	-0.90 (0.3)	18.88 (1.24)	90.75 (1.8)	Fair
4	170.1 (4.0)	2.80 (0.12)	39.71 (0.48)	1.60 (0.06)	31.62 (0.8)	83.76 (0.9)	-0.11 (0.3)	17.20 (0.65)	91.25 (2.2)	Good
5	162.25 (4.4)	2.77 (0.10)	40.07 (0.20)	1.43 (0.08)	30.44 (0.9)	83.22 (0.8)	-0.15 (0.2)	17.00 (0.84)	90 (0.0)	Fair
6	170.55 (3.7)	2.66 (0.15)	42.44 (2.3)	1.43 (0.03)	33.05 (0.4)	81.97 (1.1)	0.07 (0.2)	16.79 (0.7)	88.75 (2.8)	Fair
7	164.65 (3.2)	2.69 (0.13)	40.44 (1.3)	1.41 (0.01)	33.24 (0.2)	82.49 (0.9)	0.00 (0.2)	17.03 (0.8)	89 (2.1)	Good
8	166.75 (2.6)	2.54 (0.08)	40.94 (1.5)	1.36 (0.0)	32.87 (0.5)	82.79 (0.9)	-0.36 (0.3)	19.78 (0.74)	88.5 (2.9)	Good
9	167.55 (2.1)	2.67 (0.08)	41.01 (2.7)	1.44 (0.12)	33.64 (0.05)	84.02 (0.8)	-0.32 (0.2)	17.28 (0.75)	91.25 (2.2)	Good
10	158.45 (3.2)	2.67 (0.10)	41.16 (0.99)	1.28 (0.07)	33.56 (0.2)	82.70 (1.1)	-0.17 (0.15)	19.28 (0.8)	90 (1.6)	Fair
11	172.5 (3.00)	2.66 (0.17)	39.64 (1.4)	1.57 (0.12)	32.71 (0.1)	85.18 (1.0)	-0.65 (0.2)	17.11 (0.9)	92.25 (2.6)	Good
12	169.6 (3.6)	2.75 (0.13)	40.87 (0.63)	1.52 (0.09)	32.54 (0.4)	84.58 (0.8)	-1.01 (0.3)	20.30 (1.0)	92 (2.5)	Good
13	171.8 (5.4)	2.81 (0.04)	40.54 (0.46)	1.61 (0.09)	31.76 (0.0)	84.50 (1.1)	-0.48 (0.3)	20.32 (1.3)	90 (2.3)	Good
14	171.35 (3.5)	2.66 (0.06)	42.23 (1.3)	1.45 (0.1)	32.58 (0.4)	84.29 (1.3)	-0.72 (0.34)	21.10 (1.2)	91.75 (2.5)	Good
15	173.45 (5.2)	2.75 (0.11)	40.24 (1.6)	1.61 (0.1)	31.74 (0.5)	85.43 (0.7)	-0.99 (0.24)	19.75 (0.9)	91 (2.1)	Good
16	160.1 (4.9)	2.87 (0.05)	41.60 (0.8)	1.39 (0.09)	32.34 (1.4)	84.37 (1.2)	-0.95 (0.3)	20.16 (1.1)	88 (2.5)	Fair
HSD*	**4.21**	**0.30**	**5.61**	**0.38**	**1.47**	**0.99**	**0.25**	**0.93**	**2.38**	

* Tukey's Honest Significant Difference for means separation ($P \leq 0.05$)

[1] Standard deviation

**Subjective rating based mainly on diameter and rollability scores (day 14): Good = rollability score >3 on day 14, ≥165 mm; Fair = rollability score >3 on day 14, 157-164 mm ; Poor = rollability score <3 on day 14, any diameter.

The higher the specific volume the more fluffy the tortilla is. In general, the smaller tortillas puffed less (smaller specific volume) than larger tortillas.

Subjective rating based mainly on tortilla diameter and rollability scores (on the last day of storage, day 12) was evaluated. Tortillas were grouped into three categories (Table XIV). The categories were: good = Tortillas with diameters $\geq$ 165 mm and rollability score > 3; fair= 157-164 mm diameter with rollability score > 3; poor= any diameter with rollability score < 3. Most tortillas had “good” ratings. None of them received “poor” ratings.

Subjective rollability of wheat flour tortillas

Subjective rollability was significantly ($P \leq 0.05$) affected by storage time with decreased scores observed during storage at room temperature (Appendix, Fig.C2). However, there was only a small drop of rollability score from day 0 (fresh tortilla) compared with day 12 (stale tortilla). Due to mold contamination, the storage time was set only for 12 days. Over this time, it was not possible to see much difference in the samples. The rollability test indicated more textural differences at the end of storage than at the beginning. The difference between day 4 and day 8 was smaller than the difference between day 8 and day 12.

The lowest rollability score among the samples after 12 days of storage was 3.6. This means the tortillas were still flexible with almost no cracks and acceptable even after 12 days. This happened because all 16 wheat flours were considered strong with high protein content, and this characteristic gives higher shelf stability for these tortillas. Flexibility is considered a good quality tortilla parameter (Pascut et al 2004).

Objective rheological techniques

Two-dimensional extensibility was used to characterize wheat flour tortillas during storage. The typical curve is shown in Fig. 10. Four variables were determined, namely: deformation modulus, maximum force, rupture distance and work.

Significant changes were seen in deformation modulus for all samples. As the storage time increased, the deformation modulus tended to increase too. Changes were more pronounced at the early part of storage (from day 0 to day 4) (Appendix, Fig. C3). Fresh tortillas are more elastic than stale tortillas. It suggests that the lower the deformation modulus the more elastic a tortilla is. This technique was very sensitive for textural changes especially in the first day of storage.

Overall, maximum force did not change during storage time, thus, it was not a good indicator of changes in these 16 tortilla samples (Appendix, Fig.C4).

Rupture distance and work had similar behavior (Appendix, Fig. C5, Fig.C6). They decreased as storage time increased, opposite behavior of deformation modulus. However, the most noticeable change was between day 0 and day 4 (beginning of storage) and more pronounced in the first day of storage. These parameters correspond to tortilla extensibility. Fresh tortillas are more extensible (had higher rupture distance and work values) than stale tortillas (lower values).

In general, the objective technique was good to detect changes at the beginning of storage whereas changes at the end of storage were detected by the subjective rollability test.

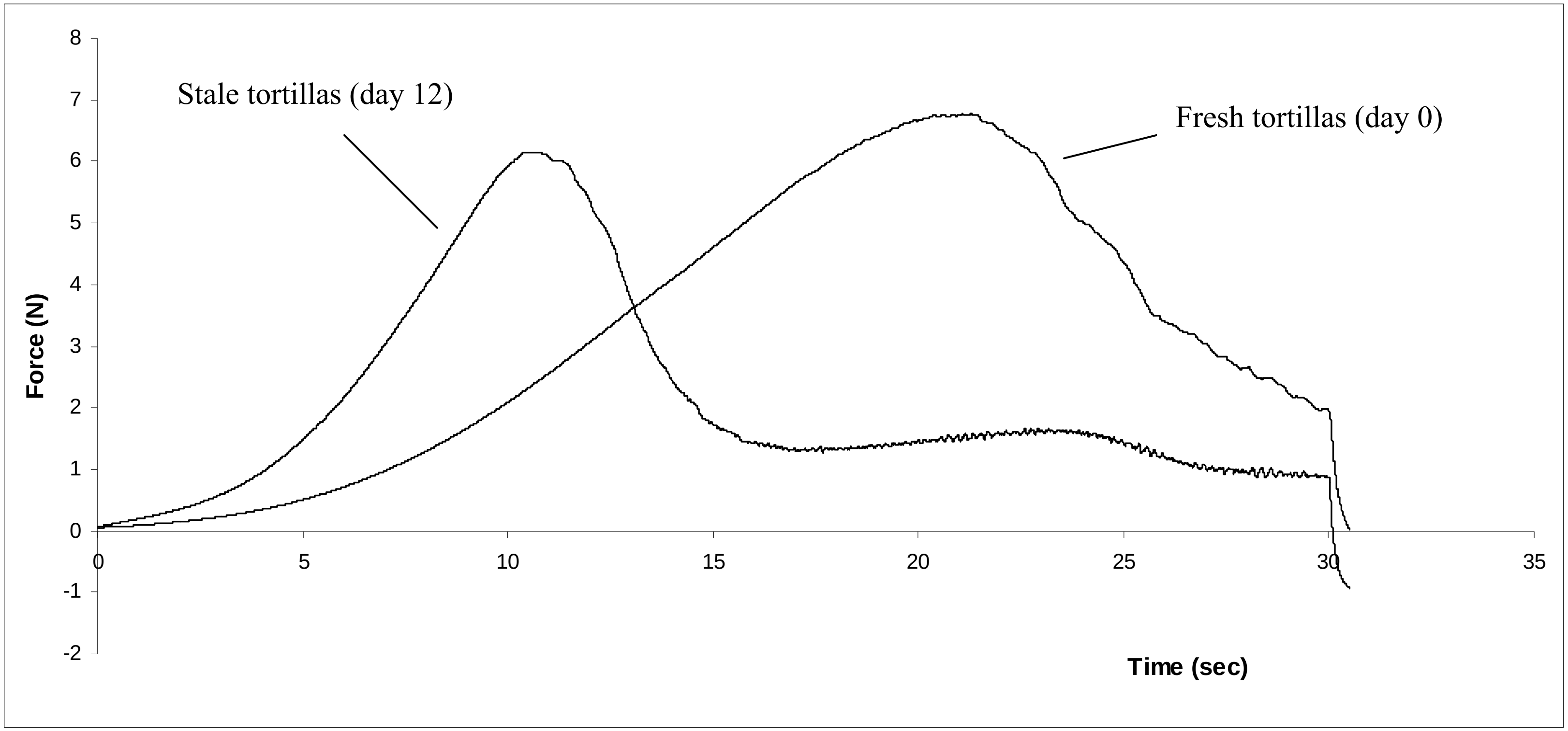


Fig.10. Typical two-dimensional extensibility curves obtained from fresh (day0) and stale (day12) wheat flour tortillas.

Simple correlation results

Sedimentation height was positively correlated with farinograph stability and breakdown time ($r = 0.57$ and 0.58, respectively, $P<0.05$) and negatively correlated with tolerance index ($r = -0.55$, $P<0.05$) (Appendix, Table C3). The hypothesis was that sedimentation test could replace farinograph and mixograph tests, however, for that set of 16 wheat flours, it correlated only with these three parameters from farinograph test, and they were not highly correlated. Sedimentation height also correlated with dough resistance to extension ($r = 0.53$, $P<0.05$), dough extensibility ($r = -0.54$, $P<0.05$), equilibrium modulus ($r = 0.57$, $P<0.05$) and highly correlated with cohesiveness ($r = 0.71$, $P<0.01$), all texture parameters.

There were also significant correlations between texture analyses (TPA, stress relaxation and dough and gluten extensibility test) and farinograph and mixograph tests (mixing properties). Except for water absorption, all farinograph and mixograph parameters were highly correlated ($P<0.01$) with dough resistance to extension. Significant correlations also occurred between gluten extensibility test (resistance to extension) with farinograph and mixograph data. Springiness (TPA test), equilibrium modulus, k1 and k2 (stress relaxation test) were significantly correlated with farinograph and mixograph parameters.

Farinograph water absorption was highly correlated with hardness (TPA) ($r = -0.65$, $P<0.01$) confirming the finding in the preliminary tests (Appendix B) wherein dough hardness significantly decreased by adding more water to make dough. Excess water was not used.

Grain/flour physical chemical characteristics and tortilla quality

Besides tortilla physical properties (diameter, color L* and specific volume), rheological properties from the two-dimensional extensibility test (deformation modulus, maximum force, work and rupture distance) at day 0 (processing day) were considered as tortilla quality parameters. The subjective rollability test is a major determinant of tortilla quality. However, the rollability scores of these 16 samples did not differentiate the samples well. Thus, this data was not included in the calculation of a prediction model. The L* value, an objective test, was used as tortilla quality indicator instead of opacity, a subjective test, since they were highly correlated ($r= 0.65$, $P<0.01$).

Flour protein content was significantly correlated with diameter, maximum force and work ($r = -0.52, 0.53, 0.57$, respectively, $P<0.05$) (Table XV). Waniska et al (2004) found a negative correlation between tortilla diameter and protein content using 61 wheat flours. Tortillas shrink-back after hot-pressing and during baking if strong flour is used. Therefore, the stronger the flour, the smaller the tortilla diameter.

High correlations ($P<0.01$) were found between flour L* and tortilla color L* ($r = 0.67$), gluten index and diameter ($r = -0.67$) and specific volume ($r = -0.73$). Flours with higher gluten index produced smaller diameter tortillas with lower specific volume. Smaller tortillas usually puff less, thus having lower specific volume. Diameter was highly correlated with specific volume ($r = 0.83$, $P<0.01$).

TABLE XV
Correlations of grain/flour physico-chemical characteristics with tortilla quality parameters

Variables	**Tortilla quality parameters**						
	Diameter	**Color L***	**Specific Volume**	**Deformation modulus**	**Maximum force**	**Work**	**Rupture distance**
Flour protein content	-0.52*	-0.24	-0.42	0.39	0.53*	0.57*	0.12
Sedimentation height	-0.42	0.40	-0.22	0.03	0.58*	0.53*	0.46
True density	0.29	-0.25	0.24	-0.10	-0.30	-0.23	-0.17
Particle size	0.05	-0.36	-0.16	0.26	-0.09	0.00	-0.25
Flour L*	-0.26	0.67**	0.01	-0.07	0.43	0.42	0.47
a*	0.16	-0.34	0.01	0.34	-0.39	-0.49	-0.72**
b*	0.07	0.26	0.06	-0.36	0.22	0.31	0.57*
Gluten index	-0.67**	-0.39	-0.73**	0.51*	0.44	0.27	-0.15
Wet gluten	-0.17	-0.21	-0.22	0.10	0.30	0.25	0.09
Dry gluten	-0.25	-0.11	-0.27	0.31	0.38	0.41	0.06
single kernel hardness	0.19	-0.39	0.01	-0.08	-0.42	-0.20	-0.19
Single kernel weight	0.05	-0.07	-0.02	-0.14	-0.09	-0.02	0.12
Single kernel diameter	0.11	-0.33	-0.02	-0.03	-0.33	-0.21	-0.15

** Correlation is significant at the 0.01 level (P<0.01)
* Correlation is significant at the 0.05 level (P<0.05)

Dough and gluten rheological properties and tortilla quality

Rheological parameters gave more significant correlations with tortilla quality than grain/flour physico-chemical characteristics (Table XVI). No significant correlation was found between dough/gluten rheological properties and rupture distance.

Most of the farinograph parameters and dough extensibility and resistance to extension were highly correlated ($P<0.01$) with tortilla quality parameters. Stress relaxation parameters had good correlation with tortilla quality. Diameter was highly correlated ($P<0.01$) with all farinograph (except water absorption), mixograph, dough resistance to extension and dough extensibility parameters.

Gluten resistance to extension was negatively correlated ($r = -0.56$, $P<0.05$) with tortilla diameter and positively correlated with maximum force ($r= 0.52$, $P<0.05$) and work ($r = 0.54$, $P<0.05$).

There was no significant correlation between gluten extensibility and tortilla quality parameters.

Gluten extensibility was evaluated because gluten is a simpler system than dough. Therefore, better correlations and predictions of tortilla quality were expected by studying gluten. However, dough extensibility tests provided better correlation with tortilla quality than the gluten extensibility test. It might be because gluten is a very simplified system, thus not showing relationships with tortilla parameters, which came from a more complex system. Dough has gluten, starch, lipids from wheat flour, water and other tortilla ingredients.

TABLE XVI
Correlations of dough/gluten rheological properties with tortilla quality parameters

Variables	Tortilla quality parameters						
	Diameter	**Color L***	**Specific volume**	**Deformation modulus**	**Maximum force**	**Work**	**Rupture distance**
Farinograph							
Water absorption	-0.35	-0.33	-0.33	0.12	0.10	0.31	0.07
Development time	-0.79**	-0.31	-0.57*	0.36	0.61*	0.74**	0.28
Stability	-0.82**	-0.17	-0.71**	0.47	0.69**	0.62*	0.13
Breakdown time	-0.82**	-0.12	-0.65**	0.42	0.76**	0.72**	0.26
Tolerance index	0.83**	0.15	0.68**	-0.47	-0.78**	-0.74**	-0.25
Mixograph							
Mix-time	-0.87**	-0.42	-0.70**	0.46	0.57*	0.57*	0.07
Mix tolerance	-0.85**	-0.38	-0.64**	0.31	0.54*	0.58*	0.19
Dough extensibility							
Resistance to extension (1)	-0.87**	-0.44	-0.85**	0.71**	0.86**	0.69**	0.03
Extensibility (2)	0.73**	0.37	0.65*	-0.57*	-0.85**	-0.71**	-0.16
Ratio (1/2)	-0.83**	-0.36	-0.75**	0.60	0.87**	0.76**	0.18
Gluten extensibility							
Resistance to extension (1)	-0.56*	-0.14	-0.31	0.34	0.52*	0.54*	0.21
Extensibility (2)	0.26	-0.09	0.17	-0.27	-0.28	-0.38	-0.12
Ratio (1/2)	-0.49	-0.07	-0.32	0.33	0.45	0.52*	0.18
TPA							
Hardness	0.23	-0.01	0.31	-0.06	-0.22	-0.34	-0.19
Cohesiveness	-0.53*	0.26	-0.24	0.27	0.36	0.27	0.02
Adhesiveness	0.56*	0.23	0.57*	-0.49	-0.58*	-0.45	-0.02
Springiness	-0.83**	-0.22	-0.76**	0.63**	0.64**	0.52*	-0.08
Stress Relaxation							
Equilibrium modulus	-0.90**	-0.44	-0.83**	0.68**	0.72**	0.60*	-0.06
Relaxation time	-0.57*	-0.31	-0.74**	0.54*	0.52*	0.47	-0.03
k1	-0.70**	-0.11	-0.67**	0.42	0.52*	0.38	-0.03
k2	-0.87**	-0.51*	-0.82**	0.65**	0.68**	0.56*	-0.07

** Correlation is significant at the 0.01 level (P<0.01)
* Correlation is significant at the 0.05 level (P<0.05)

However, gluten extensibility still had good correlations with some tortilla quality parameters such as diameter, maximum force and work. In this research, gluten extensibility took much longer to complete than dough extensibility tests because the gluten was isolated by hand washing. In the future, the gluten should be prepared by machine washing using the Glutomatic device to decrease time.

Many researchers have used the glutenin-gliadin ratio to study its role in rheological behavior of gluten and dough and bread quality parameters (Janssen et al 1996, Uthayakumaran et al 1999). Glutenins contribute to elasticity (resistance to extension) and gliadins contribute to extensibility. In this research, the ratio of resistance to extension-extensibility was taken to approximate the glutenin-gliadin ratio, which is done by isolating glutenins and gliadins through chemical analyses. This aimed to obtain the same results using a texture analyzer instead of chemical analyses. Studies have to be done in the future to prove this.

In general, the ratio of resistance to extension - extensibility (elasticity/extensibility) from dough and gluten extensibility tests had better correlations with tortilla parameters than extensibility by itself. It shows that resistance to extension was the best parameter in the correlation followed by the ratio of resistance to extension-extensibility and the last, extensibility. Dough resistance to extension-extensibility ratio had better results than the gluten ratio.

Development of prediction models for tortilla quality

Good quality tortillas are opaque, flexible, well puffed, with large diameters. Based on this, the tortilla quality dependent variables used were L* value (replacing opacity), diameter and specific volume, together with tortilla rheological parameters (deformation modulus, maximum force, work and rupture distance) taken on day 0 (fresh tortillas).

The prediction equation models were developed by stepwise multiple regression analysis using independent variables that were divided into four groups: physico-chemical grain/flour variables; farinograph and mixograph variables (representing the dough mixing properties); dough and gluten extensibility test and compression tests (TPA and Stress relaxation).

The most desirable prediction equation should have a high r^2 with a low number of quality parameters required. In addition, it is best if the selected quality parameters are measured by simple, rapid and precise techniques.

Tortilla diameter

Models including physico-chemical grain/flour, farinograph and mixograph, dough and gluten extensibility and compression data as independent variables were developed (Table XVII).

Gluten index and protein content were the independent variables selected from the grain/flour physico-chemical data. The gluten index alone gave an r^2 of 0.45 and root mean square error (RMSE) of 5.04. With protein inclusion, the r^2 increased to 0.78 with RMSE of 3.1.

Mix-time from mixograph was the only variable from the mixing tests (farinograph and mixograph) that predicted tortilla diameter.

TABLE XVII
Prediction equations for tortilla diameter

Groups	Step	Variable entered	Equation	r^2	RMSE
1-Grain/flour physical chemical data	1	Gluten Index (a)	233.32 - 0.725*a	0.45	5.0
	2	Protein (b)	300.03 - 0.797*a - 5.0*b	0.78	3.1
2-Farinograph and mixograph data (dough mixing properties)	1	Mix-time (a)	186.53 - 5.64*a	0.75	3.4
3-Dough/gluten extensibility data	1	Dough Resistance to extension (a)	190.64 - 62.18*a	0.75	3.4
4-Compression test data (TPA and Stress relaxation tests)	1	Equilibrium modulus (a)	214.41 - 1.445*a	0.81	3.0
Combination of 2 and 3		Mix-time (a) + dough resistance to extension (b)	192.13 - 3.28*a- 35.61*b	0.87	2.6

r^2 = coefficient of determination   RMSE = root mean square error

The r^2 was 0.75 and RMSE was 3.4. Exactly the same r^2 and RMSE were obtained in the extensibility test group where dough resistance to extension predicted diameter.

Equilibrium modulus from the stress relaxation test was the only variable from the compression test group that was in the model. The r^2 was 0.81 and RMSE was 3.0.

Not only protein content and mixing properties, but also extensibility test was considered an indicator of strength (Wrigley 1994). Therefore, a combination of mixing properties and extensibility tests was made. Mix-time and dough resistance to extension were the predictors for this new model with $r^2 = 0.87$ and RMSE of 2.6. This was a good model because it provided a high r^2 with only two variables.

Rheological properties explained tortilla diameter better. Dough resistance to extension was a good predictor, and was highly negatively correlated with tortilla diameter ($r = -0.87$, $P<0.01$) like all parameters that measure dough strength.

Gluten extensibility parameters were poor predictors, proving that dough properties would predict better than gluten.

Therefore, the best predictors of tortilla diameter are the mixograph mix-time on wheat flour and dough resistance to extension using the texture analyzer extensibility test.

Tortilla opacity (color L)*

Flour color L*, gluten index and protein content were the independent variables in the prediction equation model for color using the grain/flour physico-chemical data (Table XVIII). Flour color L* by itself gave an r^2 of 0.45 and root mean square error (RMSE) of 0.79.

TABLE XVIII
Prediction equations for tortilla opacity (color L*)

Groups	Step	Variable entered	Equation	r^2	RMSE
1-Grain/flour physical chemical data	1	Flour L* (a)	-83.113 + 1.808*a	0.45	0.79
	2	Gluten index (b)	-86.213 +1.921*a -0.079*b	0.66	0.64
	3	Protein (c)	-105.489*a +2.223*b - 0.09*c - 0.631*c	0.88	0.40
2-Farinograph and mixograph data (dough mixing properties)	1	No variable met the 0.05 significance level for entry into the model			
3-Dough/gluten extensibility data	1	No variable met the 0.05 significance level for entry into the model			
4-Compression test data (TPA and Stress relaxation tests)	1	k2 (a)	127.573 -40.186*a	0.26	0.92
	2	Cohesiveness (b)	143.328 -68.131*a +32.057*b	0.62	0.69
Combination of 2 and 3		No variable met the 0.05 significance level for entry into the model			

r^2 = coefficient of determination   RMSE = root mean square error

With gluten index and protein inclusion, the r^2 increased to 0.88 with RMSE of 0.40. These three variables together predicted tortilla opacity well.

There was no predictor for tortilla opacity from the dough mixing properties and extensibility groups.

Predictors from the compression test group were k2 from stress relaxation and cohesiveness from TPA test. However, the r^2 was very low at 0.26 for k2 and 0.62 for the combined k2 and cohesiveness.

Physico-chemical tests explained tortilla opacity better. As showed before, flour L* was highly correlated ($r = 0.67$, $P<0.01$) with tortilla color L*, however, protein and gluten index had no significant correlation with tortilla color L* and they entered in the model.

Specific volume

Like diameter, specific volume was predicted by gluten index and protein content from the grain/flour physico-chemical data (Table XIX).

Gluten index by itself gave an r^2 of 0.53 and root mean square error (RMSE) of 0.082. With protein inclusion, the r^2 went to 0.79 with RMSE of 0.057. Therefore, gluten index and protein content together predicted tortilla specific volume well.

Stability time from farinograph test was the only variable from the mixing tests (farinograph and mixograph) that predicted tortilla specific volume. However, a low r^2 of 0.51 and RMSE of 0.084 were obtained.

Dough resistance to extension was the predictor among the extensibility group variables and had $r^2 = 0.72$ and RMSE = 0.063.

TABLE XIX
Prediction equations for tortilla specific volume

Groups	Step	Variable entered	Equation	r^2	RMSE
1-Grain/flour physical chemical data	1	Gluten index (a)	2.746 - 0.014*a	0.53	0.082
	2	Protein (b)	3.737 - 0.015*a - 0.074*b	0.79	0.057
2-Farinograph and mixograph data (dough mixing properties)	1	Stability (a)	1.671 - 0.012*a	0.51	0.084
3-Dough/gluten extensibility data	1	Dough resistance to extension (a)	1.875 - 1.081*a	0.72	0.063
4-Compression test data (TPA and Stress relaxation tests)	1	Equilibrium modulus (a)	2.242 - 0.024*a	0.70	0.066
	2	Cohesiveness (b)	1.478 - 0.031*a +2.208*b	0.81	0.054
	3	Springiness (c)	1.358 - 0.019*a +3.207*b - 0.204*c	0.90	0.040
Combination of 2 and 3	1	Dough resistance to extension (a)	1.875 - 1.081*a	0.72	0.063

r^2 = coefficient of determination   RMSE = root mean square error

Equilibrium modulus from stress relaxation, cohesiveness and springiness from TPA test were the predictors from the compression test group. When all three variables were entered, the r^2 was 0.90 and RMSE was 0.04.

A combination of mixing properties and extensibility tests was made. Only dough resistance to extension was the predictor for this new model and there was no improvement in the extensibility model: $r^2 = 0.72$ and RMSE = 0.063.

Rheological properties explained tortilla specific volume better. This was also true of the tortilla diameter models. However, compression tests provided a better r^2 than extensibility test for tortilla specific volume.

The TPA tests had high coefficient of variability and the equilibrium modulus by itself gave an $r^2 = 0.70$ and RMSE = 0.066. Therefore, the extensibility test would be preferable to predict tortilla specific volume.

Among the physical tortilla quality parameters, diameter and specific volume were very well predicted by rheological tests, particularly by the dough resistance to extension parameter from extensibility test, which gives an idea of elasticity and dough strength.

Deformation modulus

Dough resistance to extension was the best predictor for deformation modulus; however, the prediction equation is not robust because of the very low r^2 (Table XX).

Maximum force

Very low r^2 was obtained for all prediction groups except for the extensibility group (Table XXI).

TABLE XX
Prediction equations for tortilla deformation modulus

Groups	Step	Variable entered	Equation	r^2	RMSE
1-Grain/flour physical chemical data	1	Gluten index (a)	- 0.275 + 0.008*a	0.26	0.088
	2	Dry gluten (b)	-0.975 + 0.01*a + 0.043*b	0.46	0.078
2-Farinograph and mixograph data (dough mixing properties)	1	No variable met the 0.05 significance level for entry into the model			
3-Dough/gluten extensibility data	1	Dough resistance to extension (a)	0.190 + 0.774*a	0.51	0.072
4-Compression test data (TPA and Stress relaxation tests)	1	Equilibrium modulus (a)	-0.061 + 0.017*a	0.47	0.075
Combination of 2 and 3	1	Dough resistance to extension (a)	0.190 + 0.774*a	0.51	0.072

r^2 = coefficient of determination   RMSE = root mean square error

TABLE XXI

Prediction equations for tortilla maximum force

Groups	Step	Variable entered	Equation	r^2	RMSE
1-Grain/flour physical chemical data	1	Sedimentation height (a)	-11.206 + 1.806*a	0.34	0.68
2-Farinograph and mixograph data (dough mixing properties)	1	Tolerance Index (a)	9.34 - 0.069*a	0.61	0.52
3-Dough/gluten extensibility data	1	Ratio of dough resistance to extension/extensibility	6.387 + 249.827*a	0.76	0.41
4-Compression test data (TPA and Stress relaxation tests)		Equilibrium modulus (a)	3.318 + 0.144*a	0.52	0.58
Combination of 2 and 3		Ratio of dough resistance to extension/extensibility	6.387 + 249.827*a	0.76	0.41

r^2 = coefficient of determination   RMSE = root mean square error

The ratio of dough resistance to extension-extensibility gave an r^2= 0.76 and RMSE = 0.41. The combination of mixing properties and extensibility parameters did not improve this r^2 value.

Work

Very low r^2 was obtained for all prediction groups with exception of the combination of mixing properties and extensibility parameters, which gave an r^2 of 0.69 (Table XXII). Development time from the farinograph test gave an r^2= 0.55 and RMSE = 11.06 and dough extensibility from the extensibility test gave an r^2= 0.51 and RMSE = 11.61.

Rupture distance

No predictors were found for rupture distance (No variable met the 0.05 significance level for entry into the model) (Table XXIII).

Dough rheological properties were better predictors than grain/flour physico-chemical properties for these four tortilla rheological properties. The extensibility test gave the best prediction.

Overall, the physical tortilla quality properties were better predicted by the rheological parameters based on r^2 and RMSE values. Moreover, the combination of mixing and extensibility properties helped in some cases to improve the prediction model.

For validation, the data from 18 wheat flours from the 2008 Wheat Quality Council (WQC) evaluations were used (Table XXIV).

TABLE XXII
Prediction equations for tortilla work

Groups	Step	Variable entered	Equation	r^2	RMSE
1-Grain/flour physical chemical data	1	Protein (a)	-67.348 + 11.517*a	0.33	13.59
2-Farinograph and mixograph data (dough mixing properties)	1	Development time (a)	51.33 + 2.054*a	0.55	11.06
3-Dough/gluten extensibility data	1	Dough extensibility (a)	139.829 -1.149*a	0.51	11.61
4-Compression test data (TPA and Stress relaxation tests)	1	Equilibrium modulus (a)	-8.59 +2.35*a	0.36	13.28
Combination of 2 and 3	1	Development time (a) + dough extensibility (b)	99.754 +1.393*a -0.702*b	0.69	9.62

r^2 = coefficient of determination   RMSE = root mean square error

TABLE XXIII
Prediction equations for tortilla rupture distance

Groups	Step	Variable entered	Equation	r^2	RMSE
1-Grain/flour physical chemical data	1	No variable met the 0.05 significance level for entry into the model			
2-Farinograph and mixograph data (dough mixing properties)	1	No variable met the 0.05 significance level for entry into the model			
3-Dough/gluten extensibility data	1	No variable met the 0.05 significance level for entry into the model			
4-Compression test data (TPA and Stress relaxation tests)	1	No variable met the 0.05 significance level for entry into the model			
Combination of 2 and 3		No variable met the 0.05 significance level for entry into the model			

r^2 = coefficient of determination   RMSE = root mean square error

Table XXIV
Wheat flour properties (WQC, 2008)

Variables	FLOURS																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Flour data																		
Protein (14% mb)	12.7	12.2	12.4	11.2	12.1	12.8	12.7	12.2	11.2	11.8	12.5	14.2	12.2	9.3	9.6	10.7	10.6	9.9
Farinograph data																		
Develop. time (min)	7.1	6.5	6.3	4	9.3	30.3	11	8	6.5	8.8	8.7	6.4	6.5	4.5	3	8.2	7	6
Stability (min)	17.9	13.1	15.8	10.5	28.1	39.7	25	24.3	9.8	22.4	25.9	9.5	10.8	8.1	9.1	13.1	30.9	13.5
Breakdown time (min)	16.2	13.8	11.4	9.8	30	43.5	23.3	16.3	10.1	21.3	17.3	9.1	10.5	8	8.1	13.9	32.3	14.6
Tolerance Index (FU)	15	20	28	25	2	1	5	17	37	17	20	36	33	43	28	27	15	16
Mixograph data																		
Mix-time (min)	3.88	2.38	4.75	2.88	4.38	9	4.5	9.38	2.63	4.5	5.38	2.25	2.63	3.38	3.38	3.5	4.38	2.58
Mix tolerance (scale 1-6)	3	2	5	2	3	6	3	5	2	4	5	0	2	2	2	1	4	2
Eextensibility data																		
Resistance to extension (N)- 1	0.59	0.51	0.69	0.49	0.76	1.33	0.75	0.72	0.42	1.12	0.68	0.37	0.39	0.52	0.45	0.54	0.58	0.41
Extensibility (mm) - 2	46.90	37.98	44.07	57.75	48.66	28.28	58.07	56.04	47.93	39.31	77.05	89.34	63.04	54.29	60.04	43.42	57.85	44.99
Ratio 1/2	0.013	0.013	0.016	0.008	0.016	0.047	0.013	0.013	0.009	0.029	0.009	0.004	0.006	0.010	0.007	0.013	0.010	0.009
Tortilla data																		
Diameter (mm)	156	165	160	171	157	134	153	149	174	151	155	173	170	170	165	165	165	171
Color L*	83.8	85.2	83.4	85.6	84.9	81.1	84.1	82.8	86	84.7	83.7	83.5	84.9	85.4	84.9	84.8	84.9	85.7
Specific volume (cm3/g)	1.5	1.6	1.5	1.8	1.5	1.2	1.4	1.3	1.8	1.4	1.4	1.6	1.8	1.9	1.8	1.7	1.6	1.8
Deformation modulus (N/mm)	0.7	0.7	0.7	0.6	0.7	0.7	0.6	0.8	0.6	0.8	0.7	0.6	0.7	0.7	0.7	0.6	0.7	0.6
Maximum force (N)	10.2	7.9	9.9	7.7	9.2	12.1	9.6	12.3	7.4	11.2	11	8	8.1	7.5	8.5	8.4	8.6	7.1
Work (Nmm)	97.2	59.9	95.6	57.9	77.7	142.4	99.6	140.9	66.4	118.6	121.5	76.4	58.7	51	64.2	64.9	73.7	51.2
Rupture distance (mm)	23.3	21.2	23.8	21.2	22.5	25.8	25.6	26.4	23.5	25	25.8	24.3	20.4	20.6	22.1	22.3	21.7	20.9

Only the best model (highest r^2) for each tortilla quality parameter was used. These included extensibility test parameters and combination of extensibility and mixing properties.

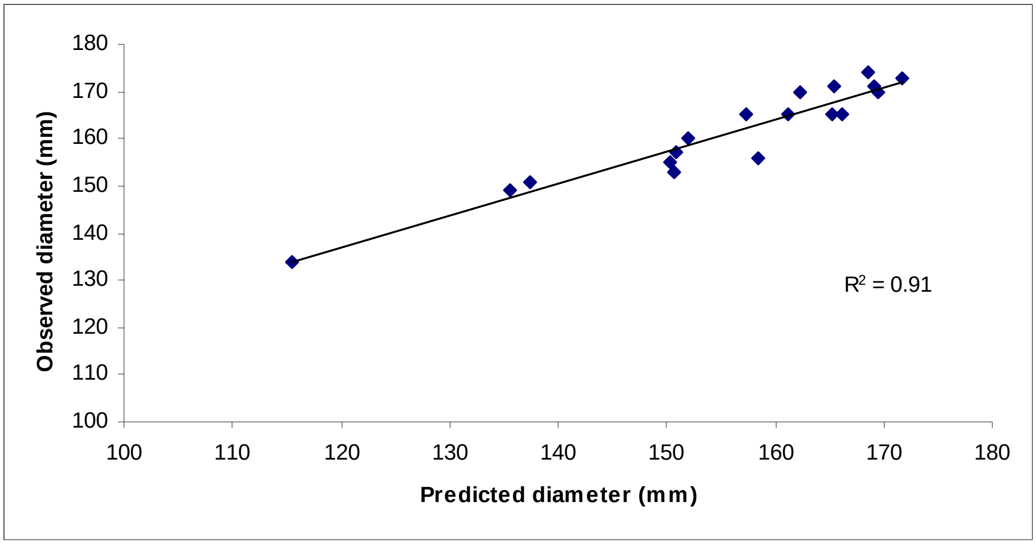
These variables were: farinograph development time, mixograph mix-time, dough resistance to extension, dough resistance to extension-extensibility ratio and dough extensibility using the extensibility test. The data used for validation are shown in Appendix, Table C4.

The validation results are presented in Fig. 11 and 12. Tortilla diameter was the parameter that had the best validation (r^2 = 0.91) followed by specific volume (r^2 = 0.64), maximum force (r^2 = 0.41), deformation modulus (r^2 = 0.25) and work (r^2 = 0.17).

The range of the independent variables used to develop the prediction models was: dough resistance to extension (0.296 - 0.538 N), dough extensibility (39.92 - 78.54 mm), ratio of dough resistance to extension-extensibility (0.00388 - 0.0127), mix-time (2.5 - 6 min) and development time (5.2 - 26.3 min).

The range used to validate the prediction model, data from WQC/2008 was: dough resistance to extension (0.37 - 1.33 N), dough extensibility (28.28 - 89.34 mm), ratio dough resistance to extension-extensibility (0.00412 - 0.0286), mix-time (2.4 - 9.38 min) and development time (3.0 - 30.3 min).

Usually, these validation models using linear regression are valid just within the range of the independent variable used to develop the model. If the value is out of this range, the error will be high. Also, tortilla rheological properties had low r^2 for prediction models, so low r^2 for validation was expected.



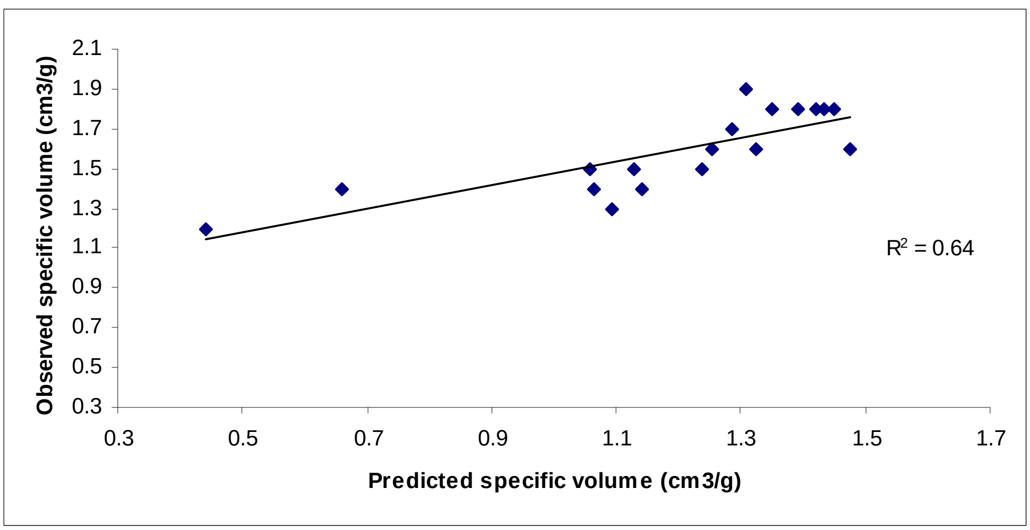


Fig. 11. Relationship between observed and predicted diameter and specific volume values

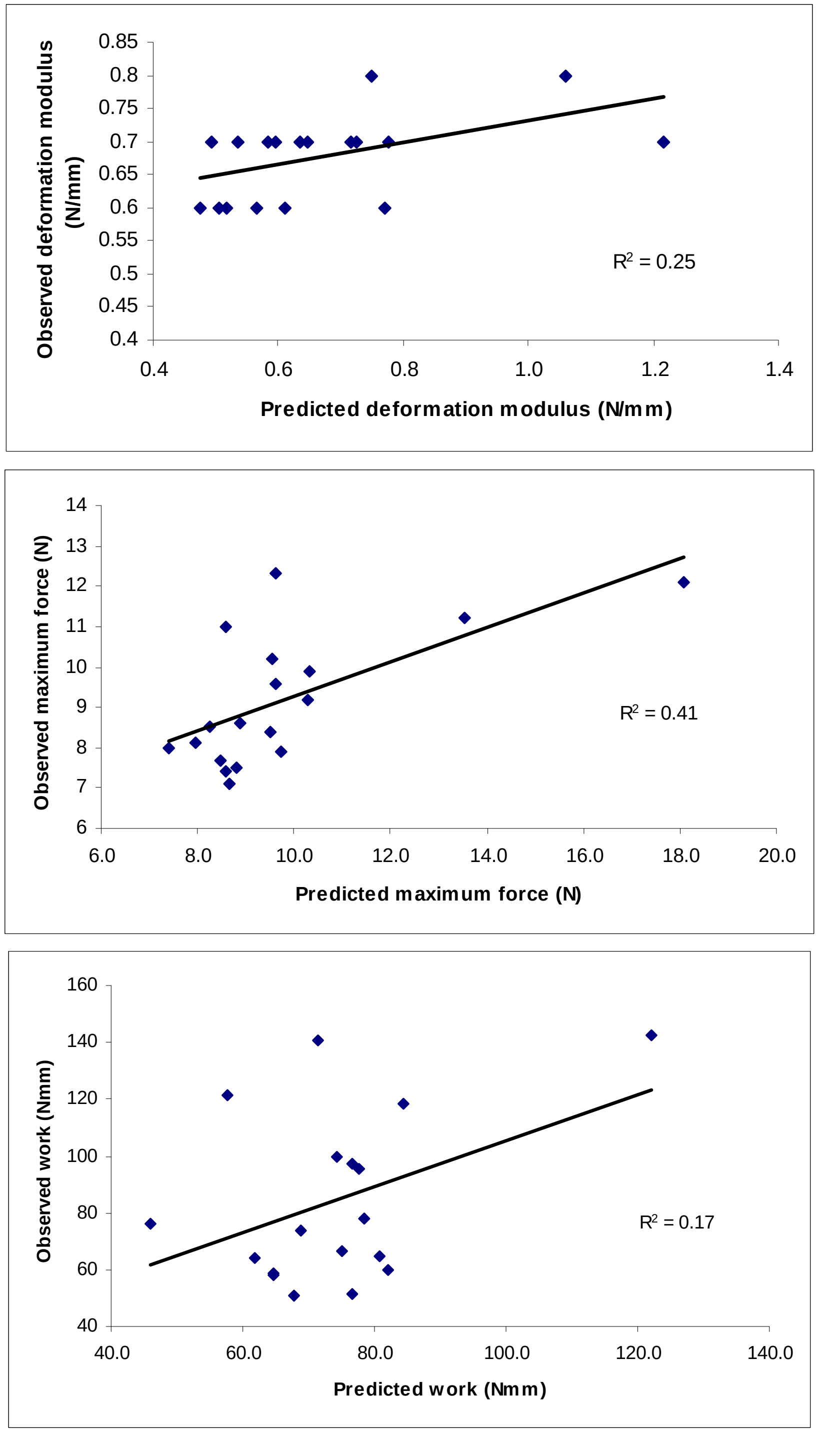


Fig.12. Relationship between observed and predicted deformation modulus, maximum force and work

Overall, considering the simplicity of the regression done, and tools used, very good prediction models, with high r^2 and low root mean square error (RMSE) were obtained using the 16 wheat flours donated by WQC, 2007. The physical tortilla quality parameters were the ones that had the best prediction models.

Validation was done using the 18 wheat flours donated by WQC, 2008. Tortilla diameter was validated with $r^2 = 0.91$. The parameters of this data set had a wider range than the 16 wheat flours. The ideal is to develop models with wide range of parameters. More wheat flours with different strengths should be used to obtain a wider range of values for parameters such as protein content, dough resistance to extension, and improve the tortilla quality models.

CHAPTER IV

RHEOLOGICAL PROPERTIES AND SHELF-STABILITY OF REFINED AND WHOLE WHEAT FLOUR TORTILLA

MATERIALS AND METHODS

One commercial hard white wheat (Farmer Direct Foods, Atchison, KS) and four wheat samples with different protein contents procured from the Texas AgriLife Research Center, Amarillo, TX were used for this study. Wheat samples were tempered to 14% moisture content and milled. A lab-scale roller mill (Brabender GmbH & Co. KG, C.W. Brabender Instruments, Inc., Hackensack, NJ) was used to produce refined flour. A hammer mill with a sieve size of 0.8 mm (Jay Bee Manufacturing, Inc. Tyler, TX) and a disc mill (at a setting of zero, minimum gap) (Laboratory Mill 3600, Perten Instruments, Huddinge, Sweden) were used to produce whole wheat flour.

Physico-chemical analyses

Single kernel moisture, hardness, diameter and weight were determined using a single kernel hardness analyzer (SKCS 4100, Perten Instruments Inc., Springfield, IL). Flour moisture and protein were determined by near-infrared reflectance (NIR) spectroscopy (model Dual 7000, Perten Instruments Inc., Springfield, IL).

Particle size distribution of flours was determined by Rotap Testing Sieve Shaker (The W.S. Tyler Co., Clevand, OH). One hundred grams of each flour was placed on a set of sieves (#20, #40, #60, #80, #100 and #200). The sieves were shaken for 5 min. The percentage of the fractions was measured from the weights left on the sieves.

Mixograph

A mixograph (National Manufacturing Co., Lincoln, NE) was used to estimate dough mixing properties. Ten grams of flour was used (14%mb). Mixing time and peak were determined (AACC method 54-40A).

Dough and tortilla preparation

Refined and whole wheat dough and tortillas were prepared as described in Chapter III (page 20) with some modifications. Instead of 500 g wheat flour, 1 kg was used to increase the number of tortillas evaluated. All the other ingredients were doubled. Mixing time and amount of water used were based on the mixograph data.

Evaluation of dough

Dough was subjectively evaluated for smoothness, softness, extensibility and force to extend after mixing. Objective rheological tests detailed in Chapter III were done for these five samples, and an alternative stress relaxation method was added.

Stress relaxation, sheeted dough method

Dough balls were selected and sheeted twice through a micronoodle sheeter (Atlas Marcato 150, Campodarsego, Italy) at a setting of one (maximum gap) to give a thickness of around 4 mm. An aluminum cylindrical probe (10 cm in diameter) was used and the sheeted dough was placed within the probe area (Fig. 13).

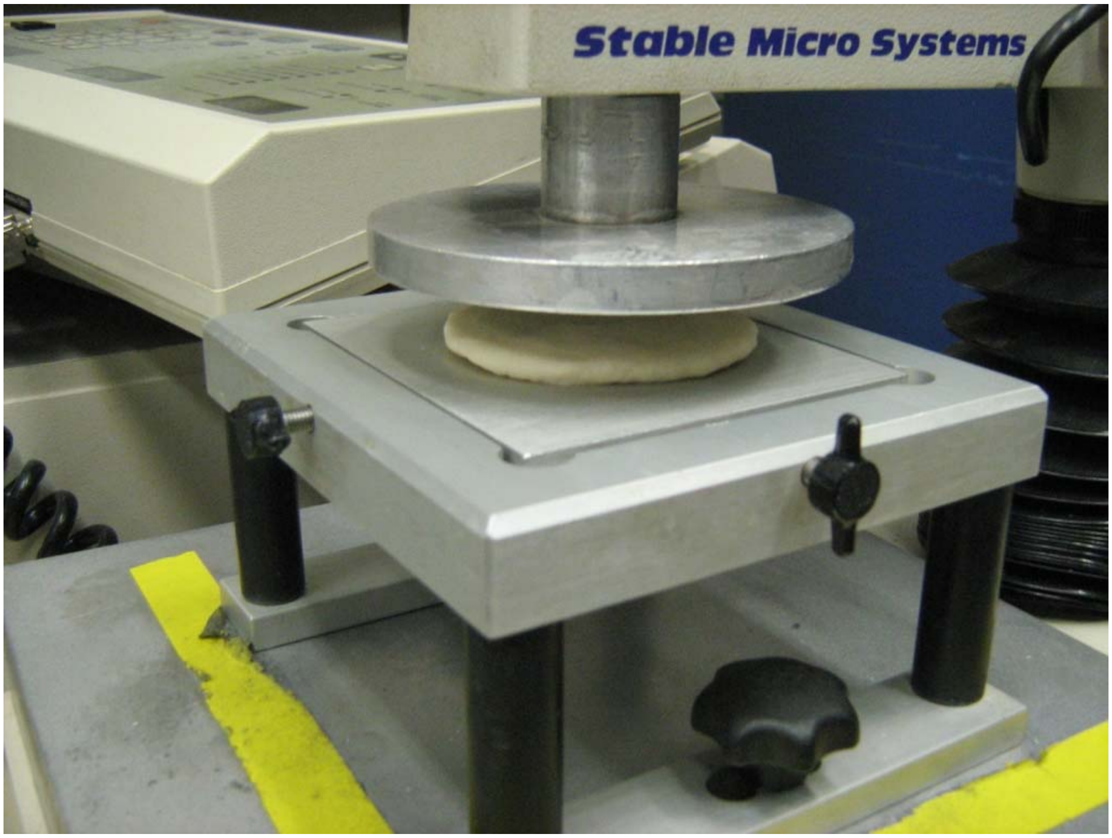


Fig. 13. Set up for the alternative stress relaxation test using a sheeted dough.

Singh et al (2006) used whole dough and dough sheet for stress relaxation studies. The setup and method given for this stress relaxation test is in Table XXV, the parameters measured and a typical graph are the same as the stress relaxation test done in chapter III (Table V and Appendix Fig.A2) using the whole dough ball. This test was done to compare with the whole dough ball method. The sheeted dough method does not need to go through the whole tortilla process to make 45 g dough balls, which means that less amount of flour and ingredients is needed.

Evaluation of tortilla

The tortillas were subjectively and objectively evaluated as in chapter III (page 37 and 38). In addition to the two-dimensional extensibility test, tensile strength or one dimensional extensibility (Suhendro et al 1999; Bejosano et al 2005), and stress relaxation (Bejosano et al 2005) were done.

The refined and whole wheat flour tortillas were evaluated objectively on the day of processing (day 0), day 1, day 4, day 8 and 14 days after processing. Their rollability was measured after 1, 4, 8 and 14 days.

One dimensional extensibility

The one dimensional tortilla extensibility test consisted of 2 clamps, the lower clamp attached to the texture analyzer platform and the upper clamp attached to the texture analyzer arm (Fig.14).

TABLE XXV
Sheeted dough stress relaxation setup for the TA.XT2i Texture Analyzer

Parameter	**Settings**	
Test mode/options	HLDD (Force relaxation)	
Parameters	Pre test speed	5 mm/s
	Test speed	2 mm/s
	Post test speed	5 mm/s
	Force	3 N
	Time	100 sec
	Data acquisition rate	100 pps
	Load cell	5 kg
Trigger	Type	Auto
	Force	0.05 N

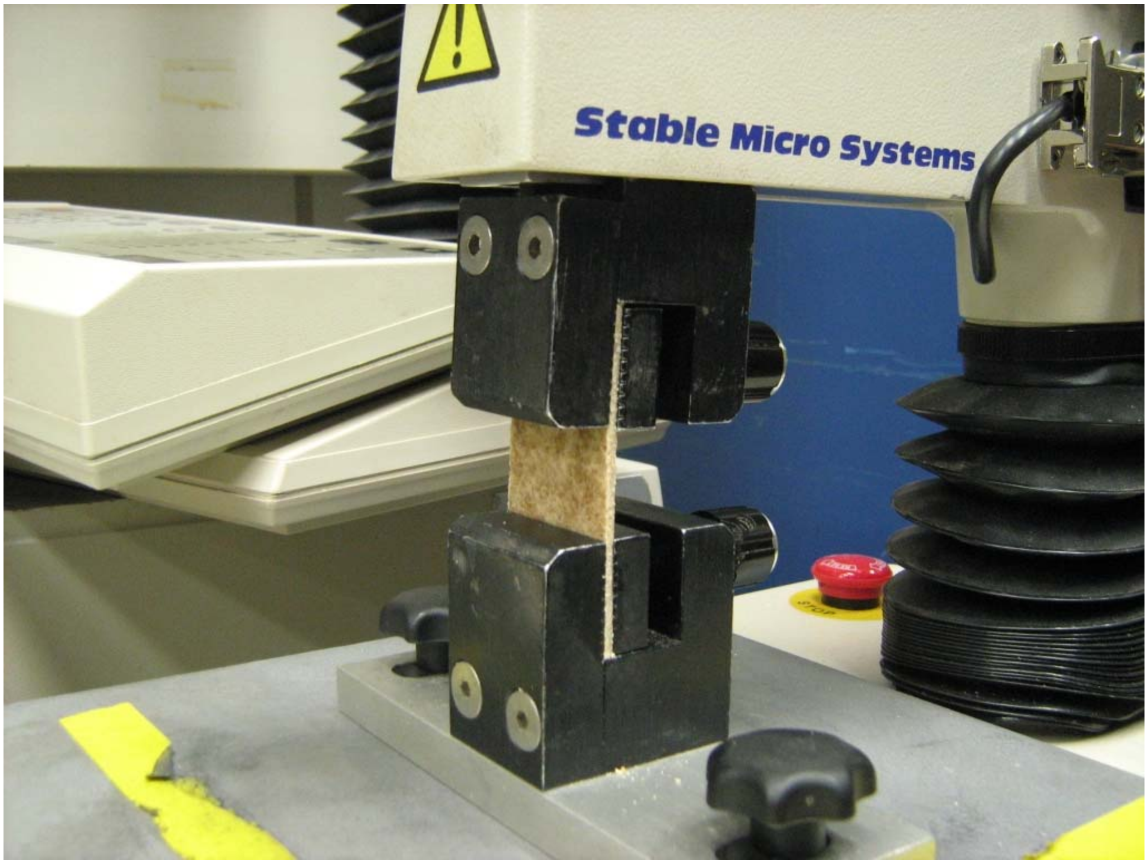


Fig. 14. Set up for the one-dimensional extensibility test

The distance between the two clamps was 22 mm. Tortilla strips were cut from the center of a tortilla using a template measuring 70 x 35 mm. The strip was aligned vertically by the two clamps.

The setup and method given for one dimensional extensibility test is in Table XXVI, and the parameters measured are defined in Table XXVII. During the test, the tortilla strip is pulled apart by tension force until it ruptures (Fig. 15). A typical one-dimensional extensibility graph is presented in Appendix, Fig.A5.

Stress Relaxation

Stress relaxation of wheat flour tortillas was done in the tension mode maintaining a constant strain (Fig. 16). The tortilla strip size and texture analyzer setup were the same as for the one-dimensional extensibility test.

The strain of 3%, linear viscoelastic region (Bejosano et al 2005; Limanond et al 2002) was used. According to these researchers, this strain level was effective for both fresh and stale tortillas. The force to maintain the constant strain versus the time data was plotted.

Like the two stress relaxation tests done for dough, the force vs. time data was fitted to Peleg and Normand’s model (Peleg and Norman, 1983). This model is applicable for deformations which lie in the linear and non-linear viscoelastic region.

$$\frac{F(0).t}{F(0)-F(t)} = \mathrm{k1} + \mathrm{k2.t}$$

TABLE XXVI
One dimensional extensibility setup and method for the TA.XT2i Texture Analyzer

Parameter	Settings	
Test mode/options	Measure force in tension: Return to start	
Parameters	Pre test speed	2 mm/s
	Test speed	1 mm/s
	Post test speed	2 mm/s
	Distance	30 mm
	Data acquisition rate	200 pps
	Load cell	5 kg
Trigger	Type	Auto
	Force	0.05 N

TABLE XXVII
Parameters recorded by one-dimensional extensibility test

Parameter	Units	Description
Extensibility modulus of deformation	N/mm	Slope of the curve
Maximum force	N	Firmness, hardness of the sample
Rupture distance	mm	Measure of the sample extensibility

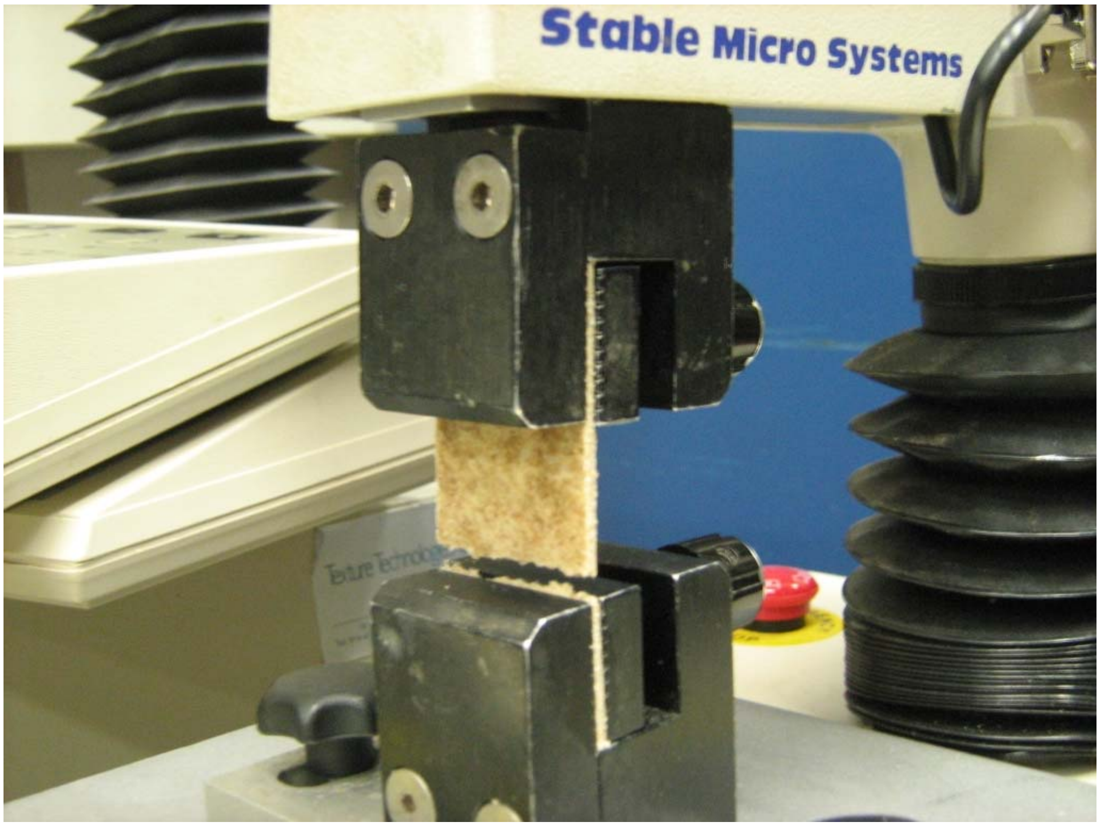


Fig. 15. A tortilla strip is pulled apart by tension force until it ruptures

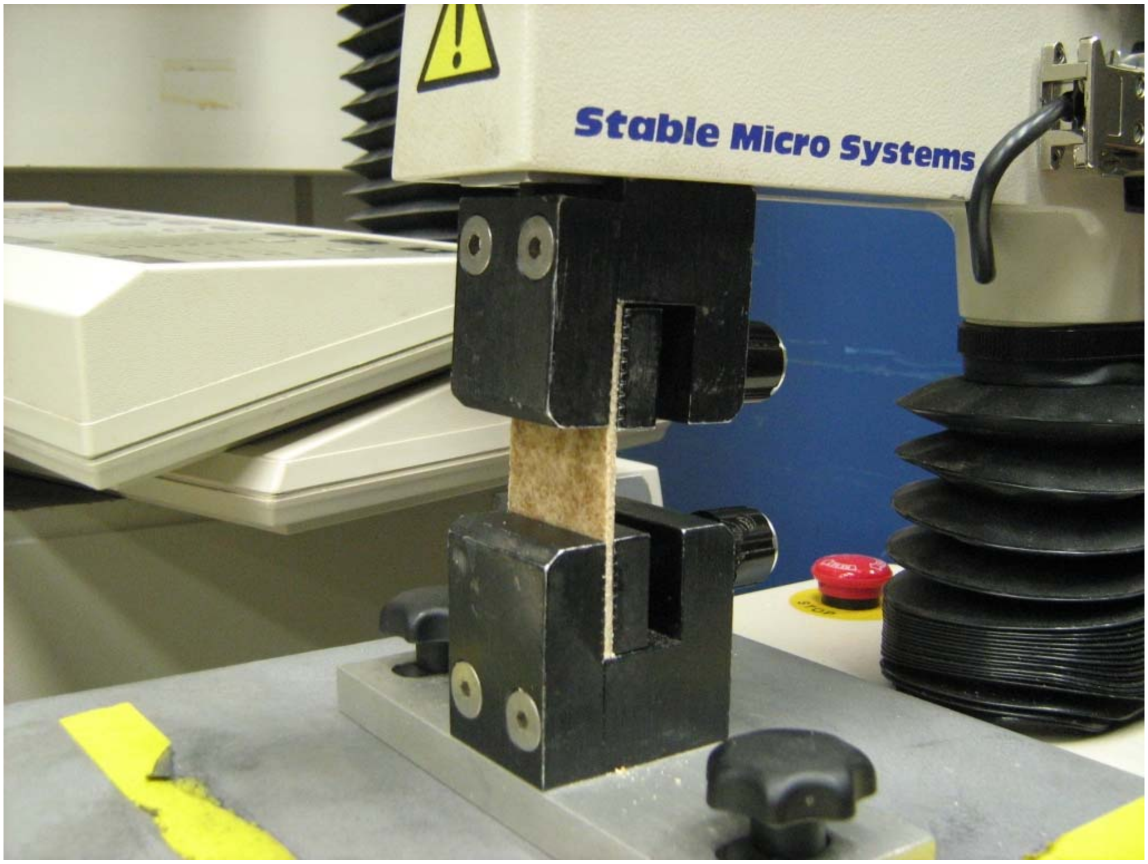


Fig.16. Set up for tortilla stress relaxation test. A constant strain of 3% is used.

The setup and method given for tortilla stress relaxation test is in Table XXVIII, and the parameters measured and typical stress relaxation graph are also similar to those presented in Chapter III (Table V and Appendix, Fig.A2).

Statistical analysis

Analysis of variance (ANOVA) was performed using SPSS v14.0 for Windows (SPSS Inc.). Differences between means were analyzed with Tukey's test with a confidence level of 95%. Grain and flour analyzes were done in duplicate in one day. Tortillas were prepared in three different days. Physico-chemical tests were analyzed as mentioned previously and for the rheological analyses, two samples were analyzed per test. Dough tests were also done on three different days, and for each test, three samples were analyzed per day.

TABLE XXVIII
Tortilla stress relaxation setup for the TA.XT2i Texture Analyzer

Parameter	Settings	
Test mode/options	Measure force in tension: Hold until time	
Parameters	Pre test speed	1 mm/s
	Test speed	1 mm/s
	Post test speed	1 mm/s
	Distance	3% strain
	Time	150 sec
	Data acquisition rate	100 pps
	Load cell	5 kg
Trigger	Type	Auto
	Force	0.05 N

RESULTS AND DISCUSSION

Physical chemical characteristics

The grain moisture content measured by SKCS ranged from 9.34 to 12.4% (Table XXIX). Kernel weight, diameter and hardness varied from 30.5 to 40.1 mg, 2.6 to 2.9 mm and 59.8 to 77.0, respectively. Hard white wheat kernels were the hardest, heaviest, and had the highest moisture and diameter values.

Flour protein content (% as-is) was measured by NIR and ranged from 11.7 (TAM 111) to 13.49% (TAM 401) (Table XXIX).

Particle size distribution for refined flours was separated into five particle-size fractions including 0.25 (#60), 0.18 (#80), 0.15 (#100), 0.074 (#200) and < 0.074 mm (Table XXX). The highest percentage of these five refined flours had particle size equal or smaller than 0.074 mm. The overall average among the five flours which had particle size in this range was 54%.

For whole wheat flours, two more fractions, 0.841 (#20) and 0.425 (#40), were separated aside from the fractions used in the refined flours. The bulk of the whole wheat flour (about 64%) had particle size between 0.25 and 0.425 mm.

Whole wheat flours had much larger particle size than refined flours. Refined flours were obtained using a roller mill, which provided much smaller particle size than hammer mill, used to produce whole wheat flour. This is due to the pericarp/bran which provides larger particle size to whole wheat flours.

TABLE XXIX
Physico-chemical properties of 5 wheat grains and flours

Parameter	TX01A5936	Hard white wheat	TAM 111	TAM 401	TX01V5314
Grain characteristics					
Moisture content (%)	9.6	12.4	10.4	9.3	9.8
Kernel weight (mg)	30.7	40.1	32.1	30.2	30.5
Kernel diameter (mm)	2.6	2.9	2.6	2.6	2.6
Kernel hardness	60.2	77.0	59.8	67.1	71.5
Flour characteristics					
Protein content (NIR)	12.5	12.5	11.7	13.5	13.3
Moisture content (NIR)	13.7	13.8	13.6	13.8	14.0

TABLE XXX
Particle size distributions (wt %) of refined and whole wheat flour *

Flour	Particle size distribution (wt%) with sieve size (mm)						
	0.841 (#20)	**0.425 (#40)**	**0.250 (#60)**	**0.180 (#80)**	**0.150 (#100)**	**0.074 (#200)**	**<0.074**
R TX01A5936	0	0	0.7 (0.07)[1]	23.1 (0.39)	10.5 (0.74)	26.9 (0.74)	33.1 (0.99)
W TX01A5936	3.8 (0.21)	47.4 (0.6)	24.0 (0.21)	12.9 (0.18)	2.9 (0.53)	1.7 (0.39)	7.8 (1.13)
R Hard white wheat	0	0	1.5 (0.07)	30.4 (0.03)	11.1 (0.6)	23.8 (1.02)	28.1 (1.2)
W Hard white wheat	3.0 (0.42)	46.4 (2.16)	23.8 (0.35)	12.7 (0.04)	3.2 (0.39)	4.0 (0.81)	9.8 (0.35)
R TAM 111	0	0	0.7 (0.07)	31.9 (0.53)	16.4 (1.02)	19.3 (1.52)	27.8 (0.57)
W TAM 111	1.7 (0.07)	38.8 (2.65)	27.1 (2.04)	24.1 (0.37)	8.9 (2.44)	2.5 (0.39)	2.8 (0.64)
R TAM 401	0	0	0.8 (0.14)	23.8 (0.81)	11.7 (0.74)	30.0 (2.02)	29.1 (1.06)
W TAM 401	1.7 (0.21)	33.7 (0.43)	24.7 (0.21)	24.5 (1.37)	7.2 (0.08)	2.7 (0.43)	2.8 (0.42)
R TX01V5314	0	0	1.2 (0.07)	31.4 (1.09)	13.8 (0.39)	27.2 (2.3)	23.2 (0.85)
W TX01V5314	6.6 (0.49)	29.7 (0.46)	26.9 (0.85)	20.7 (0.11)	7.8 (0.46)	3.5 (0.18)	6.4 (0.49)

* Values are means of two observations calculated as percent over for each sieve.

[1] Standard deviation

R- Refined flour W-Whole wheat flour

Mixing characteristics of flours

Water absorption, mix-time and peak were determined for refined and whole wheat flours (Table XXXI). The mixograms are shown in Fig.17. Mixograph water absorption varied from 61.1 (TAM 111) to 63.8% (TX01V5314) for refined flour and from 61.8 (TAM 111) to 64.3% (TX01V5314). The water absorption was determined according to the protein and moisture content of the refined flours using the mixograph manual. Whole wheat flour water absorption was determined by adding 2% above those of the refined flour. To prepare dough to make tortillas, water absorption was reduced from the mixograph results by 10% for refined flour and 4% for whole wheat flour to make suitable tortilla doughs. Mix-time varied from 3.9 (TAM 401) to 4.7 min (TX01V5314) for refined flours and from 3.8 (TAM 111) to 6.5 min (hard white wheat) for whole wheat flours.

Whole wheat flours had higher water absorption, due to the presence of fiber which competes with protein and starch for water, and longer mixing time than refined flours. In theory, the refined wheat flour produces stronger dough than whole wheat flour, because the bran particles disrupt the gluten matrix which produces a weaker dough (Lang and Walker 1990, Springsteen et al 1977). There is also a dilution of the gluten because of this higher fiber content. The lower peaks observed for whole wheat flour proved that this flour is weaker than refined flour.

TABLE XXXI
Mixing properties of 5 refined and whole wheat flours

Flour	**Mixograph properties**			**Values used during tortilla processing**	
	Water absorp. (%)	**Mix-time (min)**	**Peak (mU)**	**Water added (%)**	**Mixing time (min)**
Refined flour					
TX01A5936	62.3	4.5	5.0	52.3	4.0
Hard white wheat	62.3	4.6	5.5	52.3	5.0
TAM 111	61.1	4.0	4.9	51.1	4.0
TAM 401	63.6	3.9	5.1	53.6	4.0
TX01V5314	63.8	4.7	5.5	53.8	4.0
Overall mean	62.6	4.3	5.2	52.6	4.2
Whole wheat flour					
TX01A5936	62.9	5.5	4.1	58.9	5.0
Hard white wheat	63.2	6.5	3.8	59.2	5.0
TAM 111	61.8	3.8	4.0	57.8	4.0
TAM 401	64.0	4.8	4.0	60.0	4.0
TX01V5314	64.3	5.8	4.5	60.3	4.0
Overall mean	63.2	5.3	4.1	59.2	4.4

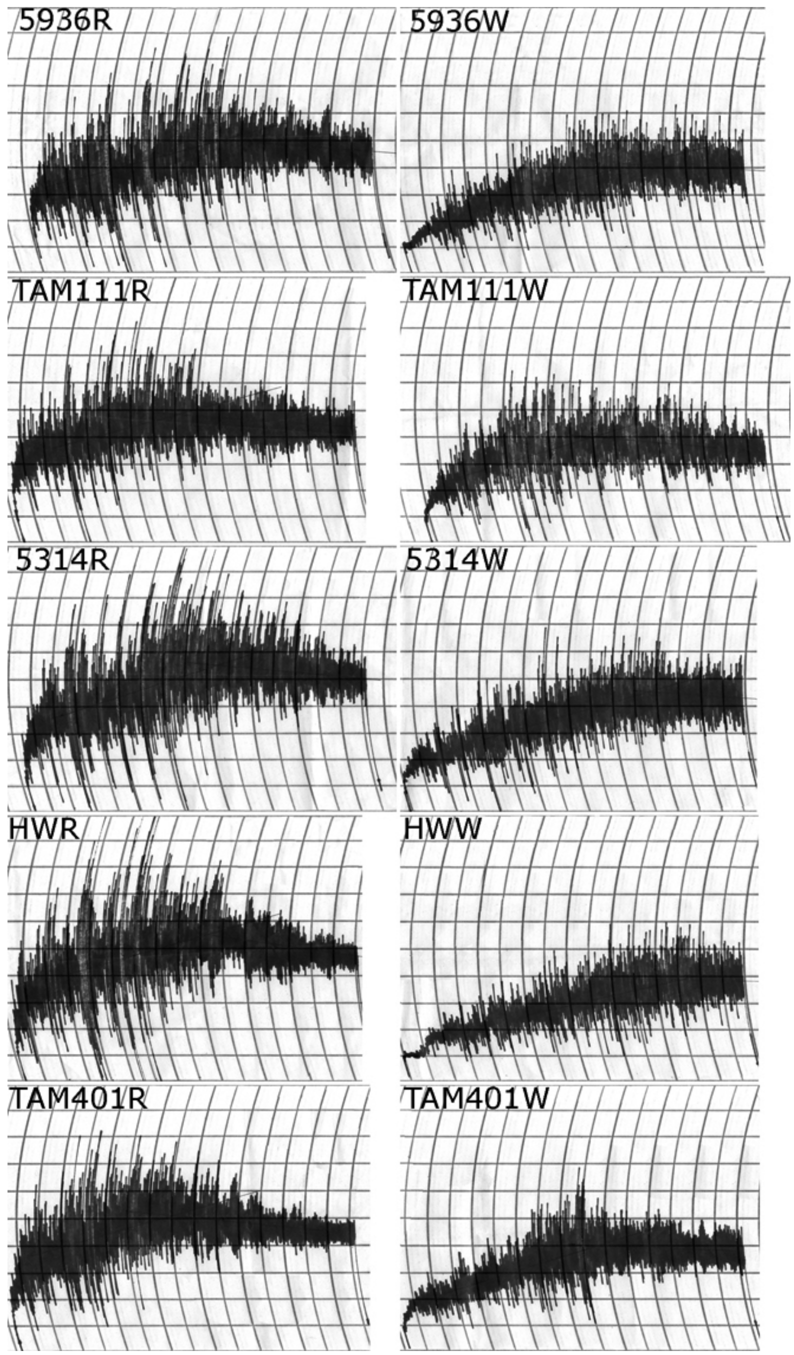


Fig.17. Mixograms of the refined and whole wheat flours

R- Refined wheat flour   W- Whole wheat flour

HW: Hard wheat; 5314: TX01V5314; 5936: TX01A5936

The commercial hard white wheat and TX01V5314 (a red wheat) were the strongest flours among the whole wheat flours because they presented the highest mixing times.

Subjective evaluation of dough properties

All refined and whole wheat doughs had the same smoothness and softness scores ($P > 0.05$) with an average score of 1.6 (very smooth to smooth) and 1.9 (very soft to soft), respectively (Table XXXII). There were significant differences ($P<0.05$) in extensibility with the refined dough having higher scores (more extensible) than whole wheat dough.

All samples had the same force to extend score for refined and whole wheat dough except for the hard white wheat where the refined dough had a higher score (more elastic) than whole wheat dough. These subjective tests indicated that refined flour doughs were more extensible than whole wheat flour doughs.

Objective methods of dough evaluation

Extensibility test

The trend observed for this test is shown in Fig. 18. For most of the samples, there was difference between refined and whole wheat dough in resistance to extension ($P<0.05$) (Fig.19).

All refined flour dough samples had higher extensibility values than whole wheat dough, agreeing with the results of the subjective tests (Fig. 20).

TABLE XXXII
Subjective evaluation of dough properties of refined flour and whole flour dough *

Flours	Variables**			
	Smoothness	**Softness**	**Extensibility**	**Force to extend**
R TX01A5936	1.5 a (0.0)[1]	1.5 a (0.0)	3.7 b (0.29)	3.5 a (0.0)
W TX01A5936	1.5 a (0.0)	1.8 a (0.29)	2.2 a (0.29)	3.3 a (0.26)
R Hard white wheat	1.5 a (0.0)	2.2 a (0.29)	2.8 a (0.29)	4.2 b (0.29)
W Hard white wheat	1.5 a (0.0)	2.0 a (0.5)	2.3 a (0.29)	3.3 a (0.29)
R TAM 111	1.5 a (0.0)	1.8 a (0.29)	3.7 b (0.29)	3.0 a (0.0)
W TAM 111	1.7 a (0.0)	2.3 a (0.58)	2.3 a (0.29)	3.0 a (0.0)
R TAM 401	1.5 a (0.0)	1.7 a (0.29)	3.5 b (0.0)	3.2 a (0.29)
W TAM 401	1.7 a (0.29)	1.8 a (0.29)	2.5 a (0.0)	3.2 a (0.29)
R TX01V5314	1.5 a (0.0)	2.0 a (0.0)	3.0 b (0.0)	3.8 a (0.29)
W TX01V5314	1.8 a (0.29)	2.3 a (0.29)	2.0 a (0.0)	3.8 a (0.29)

R: Refined flour; W: Whole wheat flour

* Means followed by the same letter in the same column between samples (refined and whole wheat) are not significantly different ($P \leq 0.05$)

** Softness: 1 – very soft, 5 – firm; Extensibility: 1 – not extensible, 5 – very extensible; Force to extend: 1 – less force, 5 – much force;

[1] Standard deviation

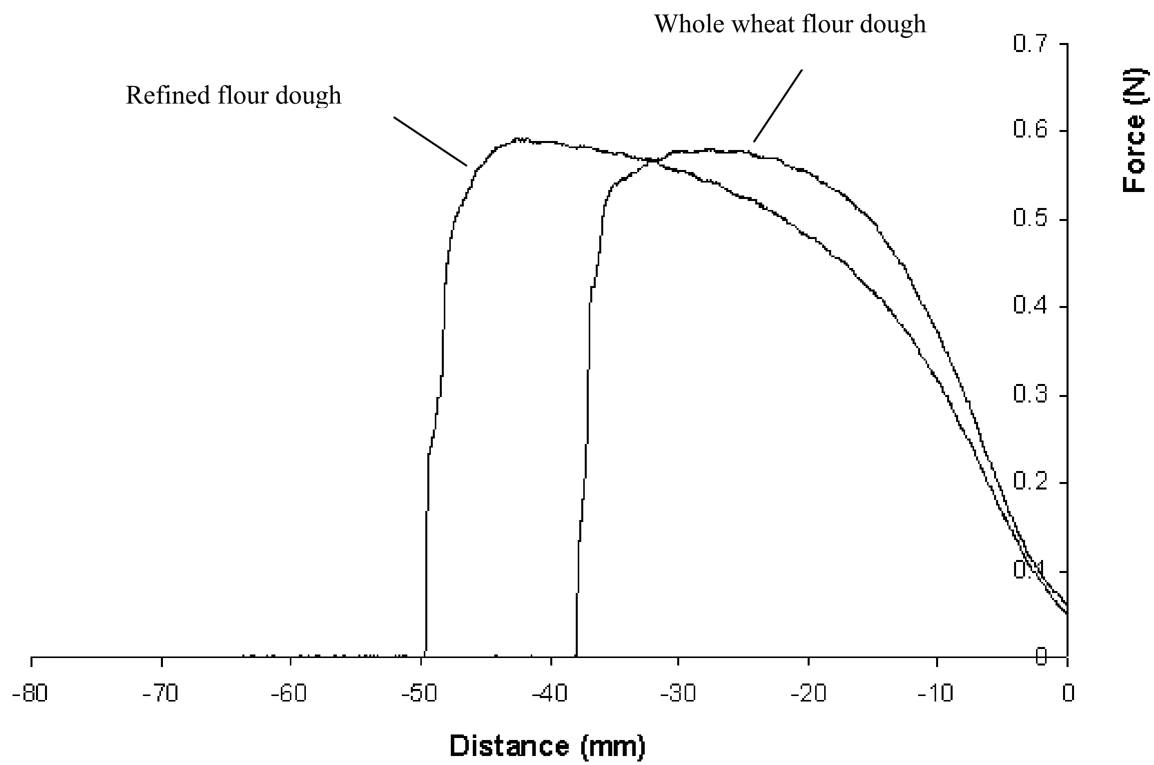


Fig. 18. Extensibility test: Trend observed between whole wheat flour and refined flour using TX01V5314 as an example

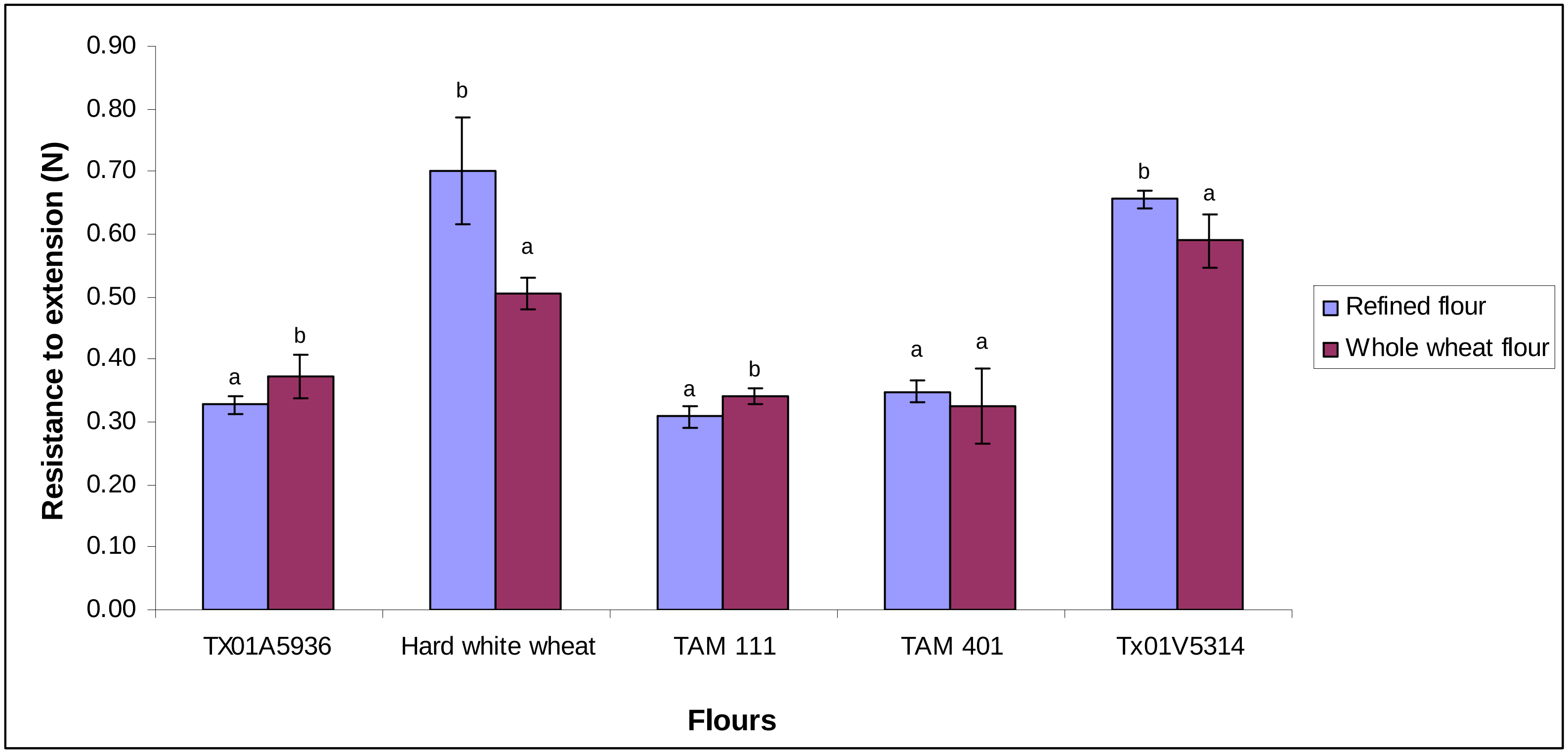


Fig. 19. Resistance to extension between refined flour dough and whole flour dough.

Values followed by the same letter for each sample are not significantly different (P≤ 0.05).

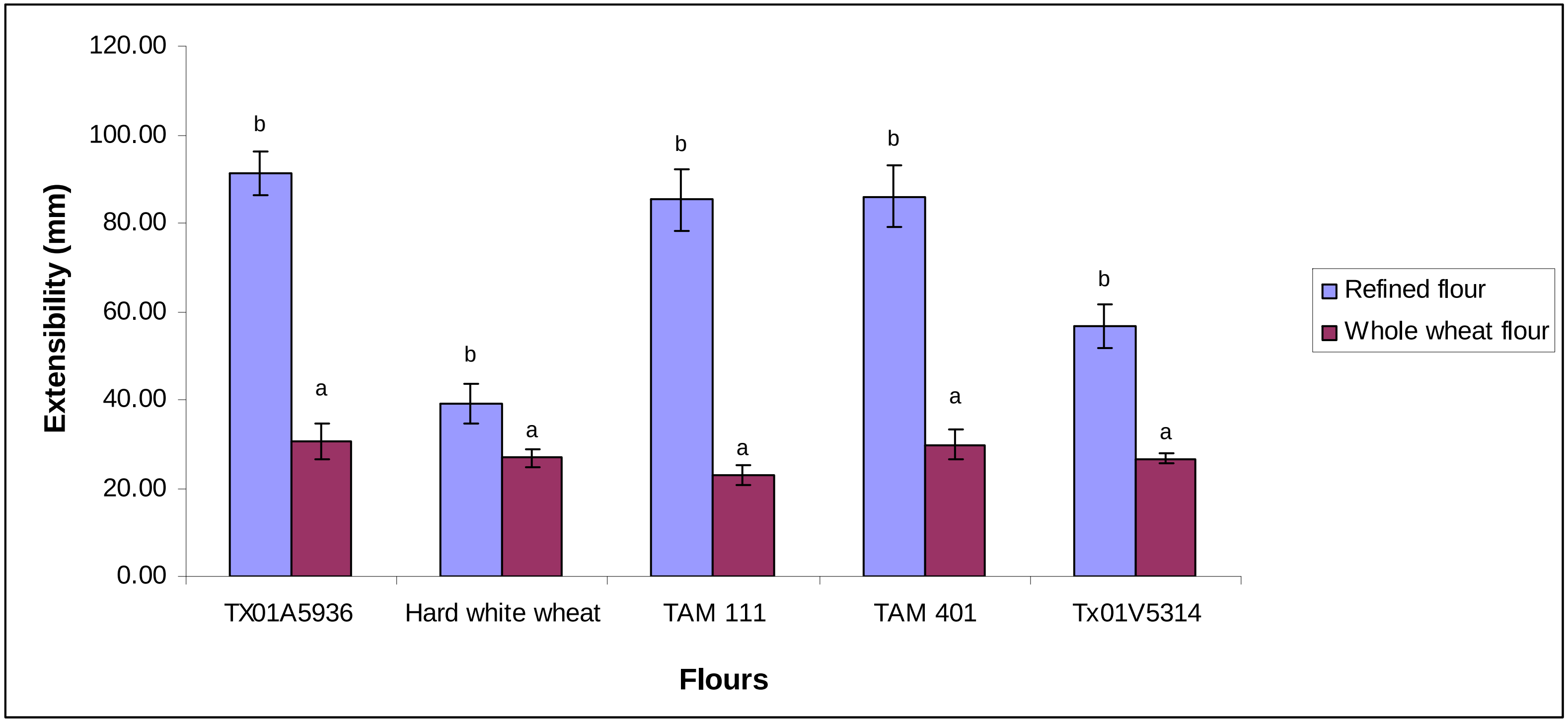


Fig. 20. Comparison of extensibility of refined and whole wheat flour doughs

Values followed by the same letter for each sample are not significantly different ($P \leq 0.05$).

The bran in whole wheat flour influenced dough rheology by decreasing its extensibility. Moreover, the particle size might be a factor that affected dough strength parameters such as mixing time and dough resistance to extension.

It was not possible to make any conclusion regarding the difference between whole and refined wheat dough in the extensibility test. However, it was clear that among the refined and whole wheat flours, the hard white wheat and TX01V5314 had higher resistance to extension (measure of strength) and lower extensibility, proving that these two samples were the strongest flours.

TPA test

There was a difference ($P<0.05$) between refined and whole wheat flour dough ($P<0.05$) (Table XXXIII). For all samples, hardness was higher for whole wheat (overall mean = 249 N) than refined wheat doughs (overall mean = 110.4 N). Refined wheat doughs had higher values for cohesiveness, springiness and adhesiveness in most samples than for whole wheat doughs.

Whole wheat doughs were drier than refined doughs. The fiber present in the whole wheat flour is the probable cause of increased hardness.

As explained in chapter III, geometry and weight of the samples as well as room temperature and relative humidity were found to be important in the TPA tests.

Stress relaxation test

Refined and whole wheat flour doughs differed in stress relaxation ($P<0.05$) (Table XXXIV).

TABLE XXXIII
Objective rheological tests: TPA test*

Flours	Hardness (N)	Cohesiveness	Adhesiveness (Nmm)	Springiness (mm)
R TX01A5936	120.8 a	0.34 a	11.3 a	3.0 a
	(7.53)[1]	(0.04)	(1.96)	(0.21)
W TX01A5936	234.7 b	0.40 b	13.4 b	3.1 a
	(3.42)	(0.02)	(0.62)	(0.07)
R Hard white wheat	130.9 a	0.40 b	8.4 b	3.9 b
	(3.80)	(0.02)	(1.90)	(0.21)
W Hard white wheat	258.3 b	0.37 a	3.6 a	3.3 a
	(17.27)	(0.01)	(0.41)	(0.14)
R TAM 111	114.7 a	0.44 b	8.0 b	2.9 a
	(10.19)	(0.09)	(1.74)	(0.40)
W TAM 111	296.1 b	0.32 a	2.1 a	2.8 a
	(24.80)	(0.02)	(0.54)	(0.16)
R TAM 401	89.7 a	0.40 b	5.1 a	3.1 b
	(12.69)	(0.07)	(1.71)	(0.14)
W TAM 401	208.9 b	0.31a	3.7 a	2.7 a
	(10.13)	(0.01)	(1.12)	(0.09)
R TX01V5314	95.9 a	0.4 b	6.0 b	4.2 b
	(8.84)	(0.02)	(2.24)	(0.14)
W TX01V5314	246.5 b	0.4 a	3.8 a	3.4 a
	(10.83)	(0.01)	(0.38)	(0.11)
R Overall mean	110.4	0.40	7.8	3.4
W Overall mean	249.0	0.36	5.3	3.1

[1] Standard deviation

* Means followed by the same letter in the same column between samples (refined and whole wheat) are not significantly different ($P \leq 0.05$)

R- Refined flour W- Whole wheat flour

TABLE XXXIV
Objective rheological tests: Stress relaxation test*

Flours	Variables			
	Equilibrium modulus (Pa)	**Relaxation time (sec)**	**k1 (sec)**	**k2**
R TX01A5936	26.02 a	1.64 a	0.794 a	1.071 a
	(0.34)[1]	(0.10)	(0.04)	(0.004)
W TX01A5936	33.05 b	1.48 a	0.888 a	1.094 b
	(0.12)	(0.04)	(0.043)	(0.002)
R Hard white wheat	31.22 a	1.84 a	1.035 a	1.092 a
	(0.10)	(0.06)	(0.04)	(0.002)
W Hard white wheat	38.88 b	1.61 a	1.054 a	1.111 b
	(0.17)	(0.26)	(0.070)	(0.002)
R TAM 111	19.98 a	1.64 a	0.785 a	1.060 a
	(0.16)	(0.08)	(0.04)	(0.002)
W TAM 111	28.80 b	1.43 a	0.875 a	1.084 b
	(0.23)	(0.18)	(0.045)	(0.004)
R TAM 401	24.18 a	1.73 b	0.793 a	1.070 b
	(0.10)	(0.02)	(0.003)	(0.001)
W TAM 401	23.97 a	1.39 a	0.806 a	1.065 a
	(0.02)	(0.02)	(0.021)	(0.002)
R TX01V5314	31.67 a	1.82 a	0.998 a	1.091 a
	(0.11)	(0.09)	(0.03)	(0.002)
W TX01V5314	36.10 b	1.70 a	1.118 b	1.103 b
	(0.21)	(0.14)	(0.010)	(0.005)
R Overall mean	26.6	1.7	0.88	1.08
W Overall mean	32.2	1.5	0.95	1.09

[1] Standard deviation

* Means followed by the same letter in the same column between samples (refined and whole wheat) are not significantly different ($P \leq 0.05$)

R- Refined flour W- Whole wheat flour

For all samples except TAM 401, equilibrium modulus and k2 values were higher for whole wheat than refined wheat dough. For most samples, relaxation time and k1 were the same for whole and refined wheat doughs.

As explained in chapter III, the higher the equilibrium modulus and relaxation time the more elastic (stronger) the sample. The whole hard white wheat and the whole red wheat (TX01V5314) had the highest equilibrium modulus and relaxation time values, showing that they are stronger than the other flours. The same conclusion was obtained in the mixograph and extensibility tests. Nothing could be concluded about differences between refined and whole wheat flour. They are two completely different systems with different particle size and compositions.

Correlation between stress relaxation methods

Stress relaxation method 1 (whole dough ball) and method 2 (sheeted dough) parameters are shown in Appendix, Table C5. Simple correlations were done between both methods (Table XXXV).

Equilibrium modulus of method 1 had a lower variability (CV = 0.4- 6.6%) than in method 2 (CV = 1.5 - 33.3%). Equilibrium modulus was higher for whole wheat dough with method 1, but they tended to be the same in method 2. Relaxation time in method 1 also had lower variability (CV = 0.9 - 15.9%) than method 2 (CV = 2.5- 45%). Method 1 generally had the same value for refined and whole wheat dough whereas in method 2, whole wheat dough had greater relaxation time than refined wheat.

TABLE XXXV
Correlations of variables from dough stress relaxation methods 1 (whole dough ball) and 2 (sheeted dough)

Method 1 dough ball	**Method 2 sheeted dough**			
	Refined flour dough			
Refined flour dough	Equilibrium modulus (Pa)	Relaxation time (sec)	k1 (sec)	k2
Equilibrium modulus (Pa)	0.093	-	-	-
Relaxation time (sec)	-	-0.683	-	-
k1 (sec)	-	-	0.242	-
k2	-	-	-	-0.224
Whole wheat flour dough	Whole wheat flour dough			
	Equilibrium modulus (Pa)	Relaxation time (sec)	k1 (sec)	k2
Equilibrium modulus (Pa)	0.279	-	-	-
Relaxation time (sec)	-	0.179	-	-
k1 (sec)	-	-	0.621	-
k2	-	-	-	0.326

** Correlation is significant at the 0.01 level (P<0.01)
*   Correlation is significant at the 0.05 level (P<0.05)

There were no significant correlations among Method 1 and Method 2 parameters (Table XXXV). Therefore, the use of dough ball for the stress relaxation test is recommended, since it has lower variability between replicates.

Tortilla physical tests

The set of samples evaluated is presented in Fig. 21. Diameter, thickness, weight, specific volume, moisture, color (L*, a* and b*), and opacity are in Table XXXVI.

For all samples, except TAM 111, the whole wheat flour tortillas had larger diameter (mean = 184.8 mm) than refined wheat flour tortillas (mean = 173.8 mm). The refined flour tortillas were thicker (mean = 2.15 mm; whole flour tortilla mean = 1.73 mm) and lighter in color (L* mean = 84.1 and whole flour tortilla = 64.7). Most of the refined flour tortillas had higher specific volume than whole wheat flour tortillas. For color a*, b*, the whole wheat tortillas had higher values than refined flour tortillas.

TAM 111 had low mixing time, peak and resistance to extension values. It was considered a weak wheat flour. These kinds of flours have a weaker gluten structure, which allows greater extensibility. This explains the larger tortilla diameter for TAM 111. On the other hand, smaller tortillas were produced from the hard white wheat which had high mixing time, peak and resistance to extension and had a low extensibility due to stronger gluten structure.

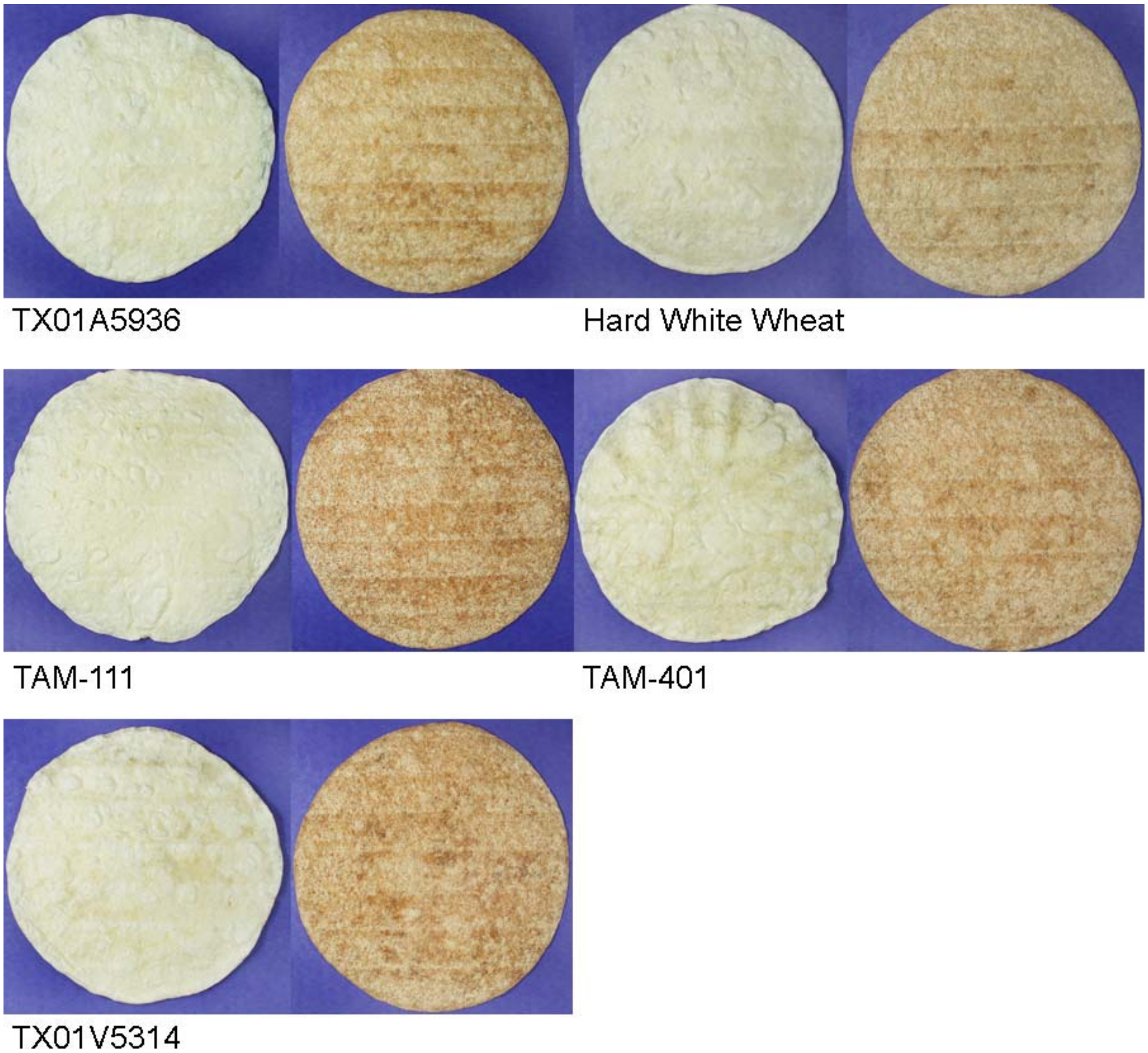


Fig.21. Refined wheat and whole wheat tortillas used in this study

TABLE XXXVI
Tortilla physical properties *

Flours	Variables									
	Diameter (mm)	Thickness (mm)	Weight (g)	Specific volume (cm^3/g)	Moisture (%)	L*	a*	b*	Opacity (%)	Rating**
R TX01A5936	177.5 a	2.23 b	40.08 a	1.41 b	34.99 b	85.71 b	-1.70 a	19.04 a	83.3 b	Good
	(3.4)[1]	(0.11)	(0.92)	(0.03)	(0.99)	(0.66)	(0.95)	(0.92)	(2.4)	
W TX01A5936	186.1 b	1.77 a	41.4 a	1.20 a	31.52 a	69.63 a	4.80 b	22.83 b	71 a	Poor
	(2.49)	(0.08)	(0.66)	(0.04)	(1.40)	(1.53)	(1.17)	(1.39)	(3.57)	
R Hard white wheat	164.5 a	2.35 b	39.9 a	1.25 b	35.86 a	84.09 b	-0.66 a	17.15 a	84.3 b	Fair
	(3.21)	(0.07)	(0.62)	(0.09)	(2.40)	(0.74)	(0.99)	(0.64)	(2.2)	
W Hard white wheat	179.7 b	1.72 a	42.5 b	1.03 a	35.74 a	67.57 a	4.62 b	22.15 b	72.7 a	Good
	(2.48)	(0.08)	(0.75)	(0.03)	(1.18)	(1.52)	(1.12)	(1.12)	(2.54)	
R TAM 111	185.6 a	1.94 b	38.9 a	1.38 b	31.60 a	84.90 b	-1.22 a	18.81 a	83.8 b	Poor
	(3.72)	(0.07)	(0.32)	(0.06)	(1.58)	(0.78)	(0.87)	(1.46)	(2.15)	
W TAM 111	186.97 a	1.72 a	40.4 a	1.19 a	31.29 a	62.95 a	6.82 b	19.52 b	69.3 a	Poor
	(2.57)	(0.04)	(2.01)	(0.06)	(1.03)	(2.02)	(1.22)	(1.04)	(1.73)	
R TAM 401	175.2 a	2.07 b	40.51 a	1.26 a	35.09 b	83.16 b	-0.89 a	20.53 a	79.5 b	Good
	(3.03)	(0.13)	(1.09)	(0.09)	(0.90)	(0.91)	(0.95)	(1.46)	(1.53)	
W TAM 401	192.6 b	1.67 a	41.6 a	1.19 a	32.35 a	63.26 a	7.09 b	21.23 b	64 a	Poor
	(2.44)	(0.03)	(0.42)	(0.002)	(1.08)	(2.51)	(1.51)	(1.27)	(2.03)	
R TX01V5314	166.4 a	2.18 b	40.98 a	1.19 a	36.04 b	82.51 b	-0.35 a	19.11 a	80 a	Good
	(3.87)	(0.17)	(1.0)	(0.08)	(0.17)	(0.73)	(0.90)	(0.92)	(0.0)	
W TX01V5314	178.9 b	1.77 a	40.8 a	1.08 a	32.34 a	60.60 a	6.97 b	20.69 b	80.5 a	Good
	(4.02)	(0.09)	(0.43)	(0.09)	(1.61)	(1.67)	(1.17)	(0.91)	(1.53)	
R Overall mean	173.8	2.15	40.1	1.3	34.7	84.1	-0.96	18.9	82.2	-
W Overall mean	184.8	1.73	41.3	1.1	32.6	64.7	6.1	21.3	71.5	-

[1]Standard deviation R- Refined flour W- Whole wheat flour; *Means followed by the same letter in the same column between samples (refined and whole wheat) are not significantly different ($P \leq 0.05$) ; **Subjective rating based mainly on diameter and rollability scores (day 14): Good = rollability score >3 on day 14, $\geq$165 mm; Fair = rollability score >3 on day 14, 157-164 mm ; Poor = rollability score <3 on day 14, any diameter.

As mentioned before, whole wheat flours are weaker than refined flour because of the high bran content which weakens the gluten network. This was the reason why whole wheat flour tortillas were larger and thinner than refined flour tortillas. Wang and Flores (1999b) also observed that tortillas made from bran flours had the largest diameters.

Subjective rating based mainly on tortilla diameter and rollability scores (on the last day of storage, day 14) was evaluated. Tortillas were grouped into three categories, namely: good = Tortillas with diameters ≥ 165 mm and rollability score > 3; fair= 157-164 mm diameter with rollability score > 3; poor= any diameter with rollability score < 3.

Most refined tortillas had "good" ratings but TAM 111 received a "poor" rating. As explained before, it was the weakest wheat flour studied. On the other hand, most whole flour tortillas had "poor" ratings. Only the strong flours, hard white wheat and TX01V5314 had "good" ratings. Therefore it is expected that whole wheat flour tortillas have a shorter shelf-stability than refined wheat tortillas. But good quality whole wheat tortillas can be produced by using strong flours like the hard white wheat and TX01V5314 samples used in this study. They provided larger tortillas with longer shelf stability.

Subjective rollability and objective rheological techniques for wheat flour tortillas

Subjective rollability and objective rheological results for all samples over storage time are shown in Appendix, Table C6-C10.

Subjective rollability

Subjective rollability scores of refined and whole wheat flour tortillas significantly decreased over storage time at room temperature (Fig.22). This means that the tortillas lost their flexibility during storage. The whole wheat flour tortillas had shorter shelf stability than refined wheat flour tortillas. They broke more quickly than refined flour tortillas. Similar result was obtained by Friend et al (1992). The loss of the gluten structure integrity due to bran from whole wheat flour drives the product to be less stable.

Subjective rollability scores were not sensitive enough to differentiate among samples within 0 to 1 day of storage.

After 8 days of storage all refined wheat flour tortillas had a rollability score above 3.0 (acceptable tortillas). All whole wheat flour tortillas had rollability scores equal or above 3.0 except TAM 111 (1.50) and TAM 401 (2.8).

After 14 days of storage (last day), TAM 111 refined flour tortilla had a score of 1.8 and it was the only one that had a rollability score below 3.0. Among the whole wheat flour tortilla samples, the only ones which kept the rollability score above 3.0 were hard white wheat (score =3.1) and TX01V5314 (score = 3.4) which were the strongest flours.

Weaker flours, such as whole wheat flours and TAM 111 and TAM 401 had shorter shelf-stability. This technique is very simple and produces reliable textural changes during storage. However, it is more sensitive after the 4th day of storage.

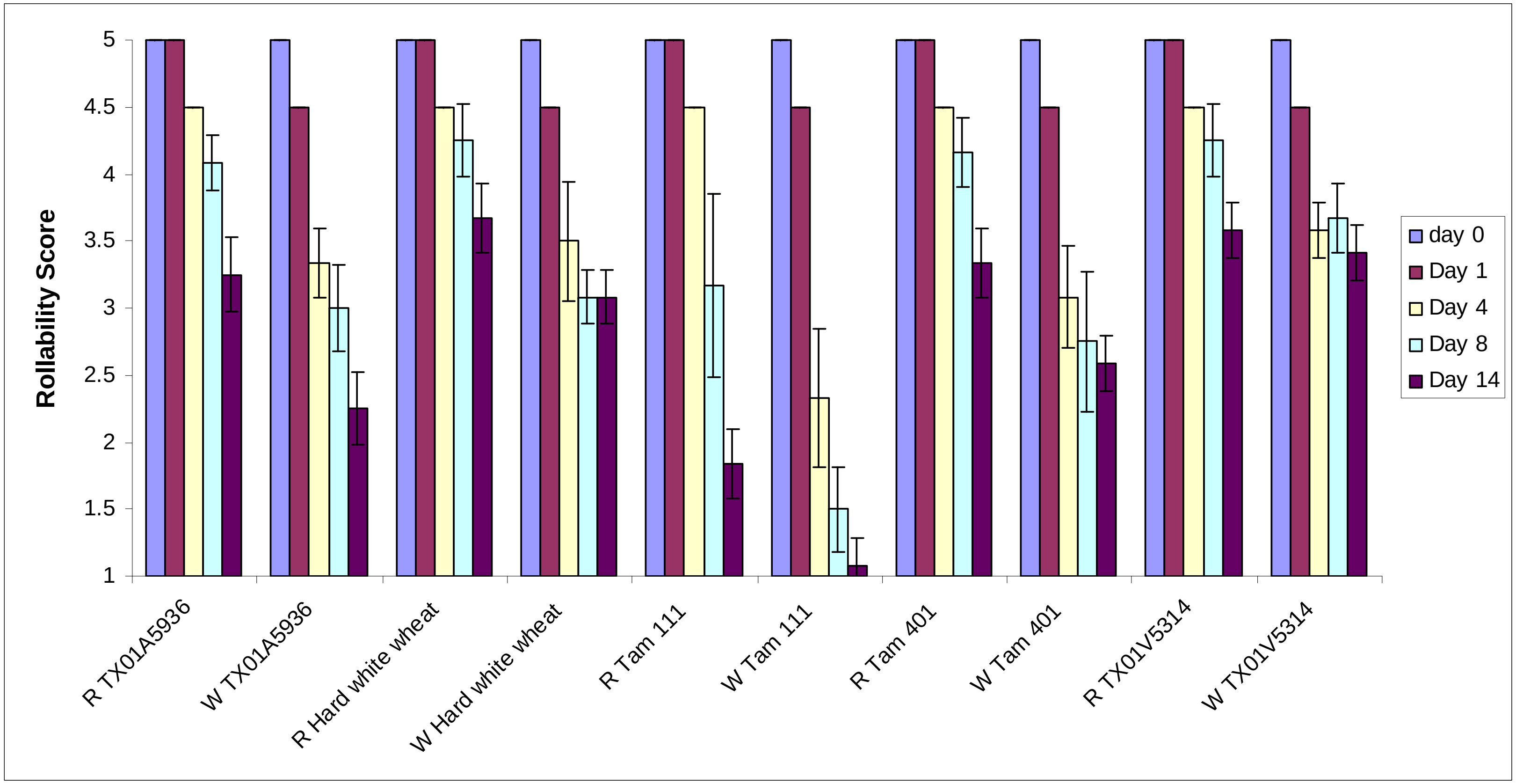


Fig. 22. Effect of storage time on rollability score of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

Two-dimensional extensibility

Deformation modulus

Deformation modulus increased over time (Fig 23), but no significant changes were observed on the first 4 days of storage for all refined and whole wheat flour tortillas.

Similar behavior was observed for subjective rollability. The results showed that stale tortillas have higher deformation modulus than fresh tortillas which mean that fresh tortillas are more elastic. Similar result was obtained in Chapter III.

Refined and whole wheat flour tortilla had similar deformation modulus values over storage time.

Maximum force

Maximum force was not a good parameter to characterize and explain changes in refined and whole wheat flour tortillas over storage time (Fig.24).

Rupture distance

For all samples, rupture distance decreased over time (Fig. 25), confirming that tortillas lose their extensibility when they stale. Significant changes in both refined and whole wheat flour tortilla texture were observed the first 4 days of storage. It was significant even after 1 day of storage. This is a very important result because subjective rollability detected changes in the samples after 4 days of storage, and rupture distance was sensitive enough to indicate textural changes from day 0 to day 4. This is an objective parameter that can be used to study changes in tortillas at the beginning of storage.

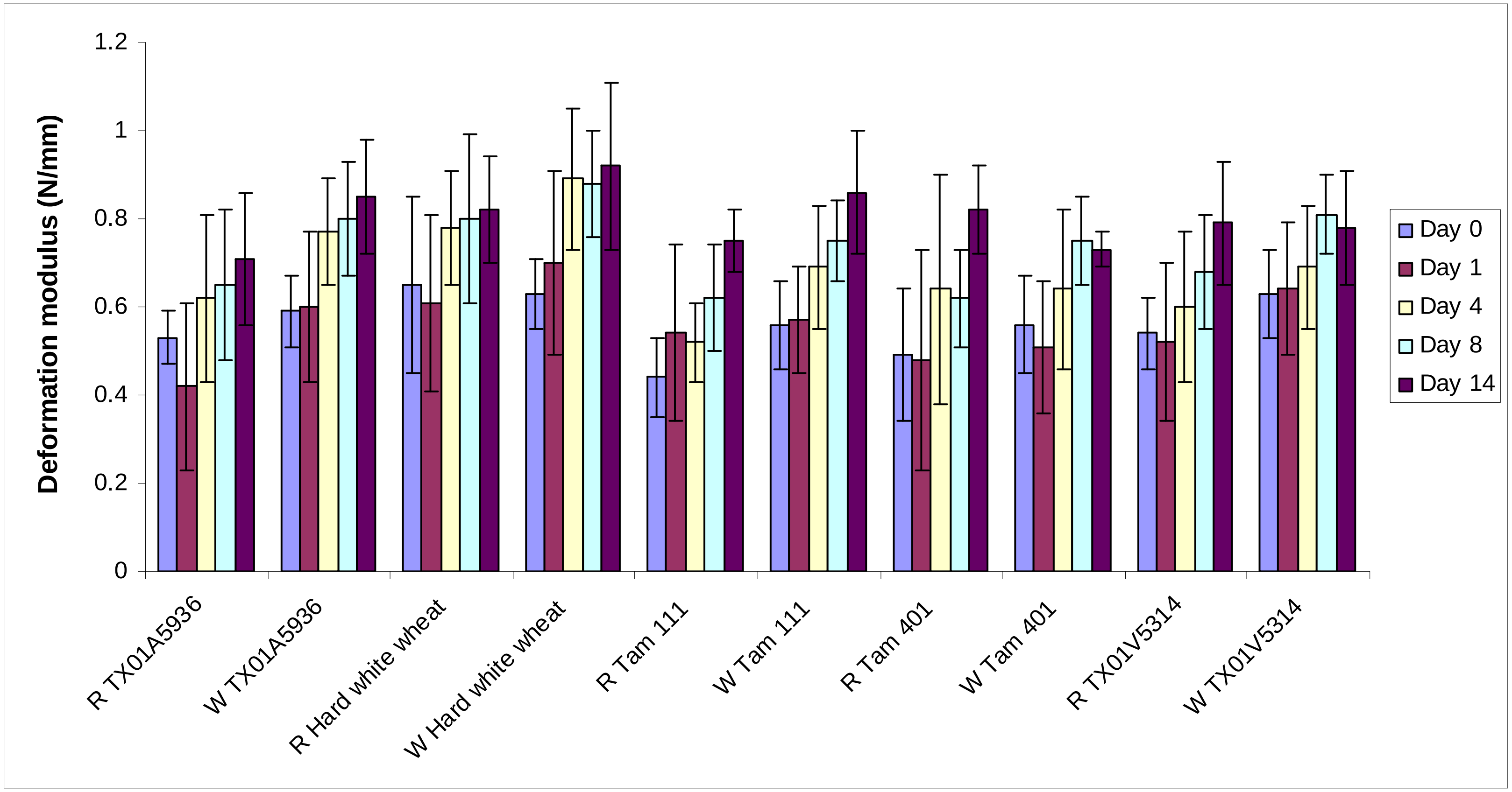


Fig. 23. Effect of storage time on deformation modulus (two-dimensional extensibility) of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

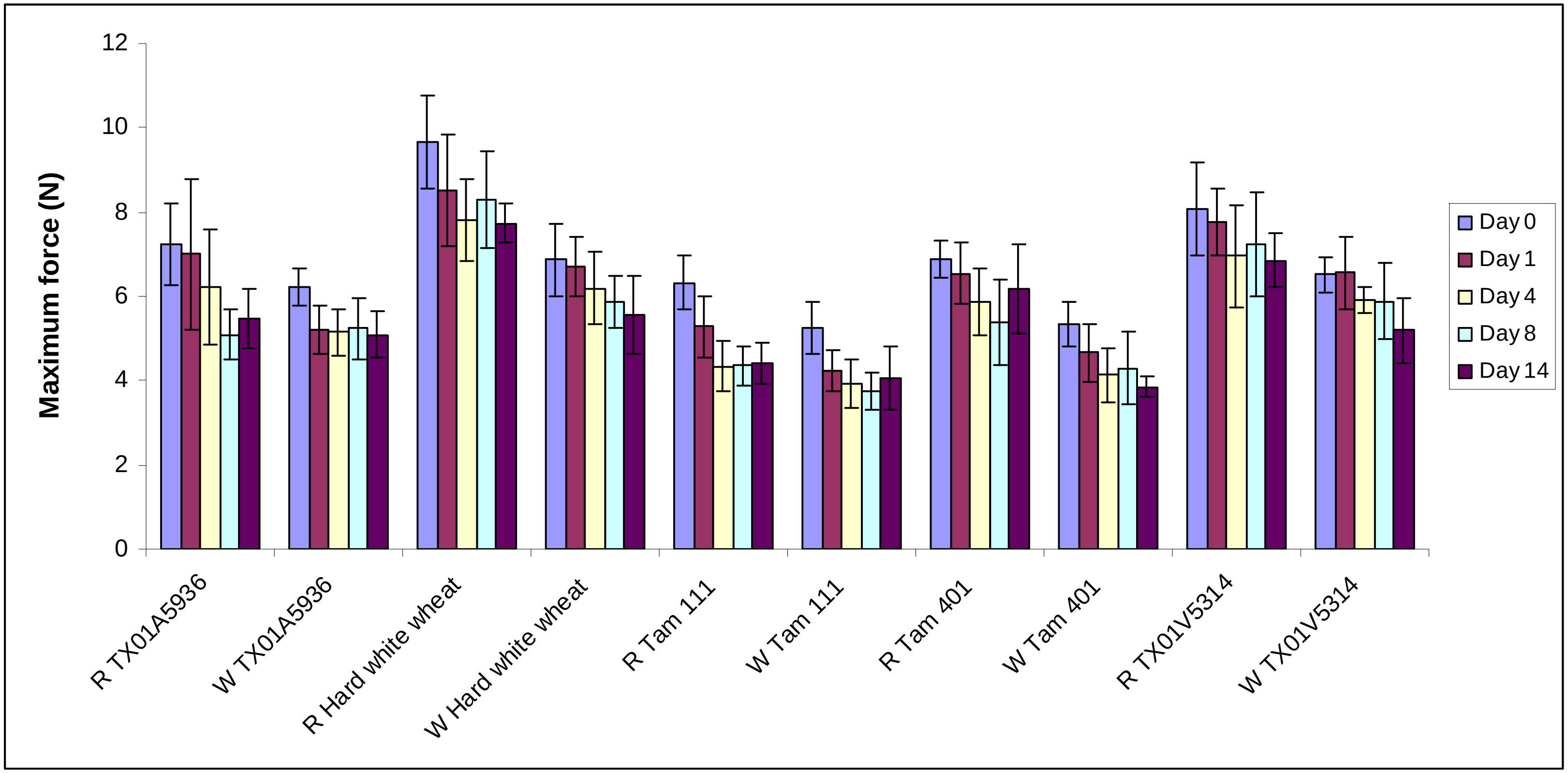


Fig. 24. Effect of storage time on maximum force (two-dimensional extensibility) of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

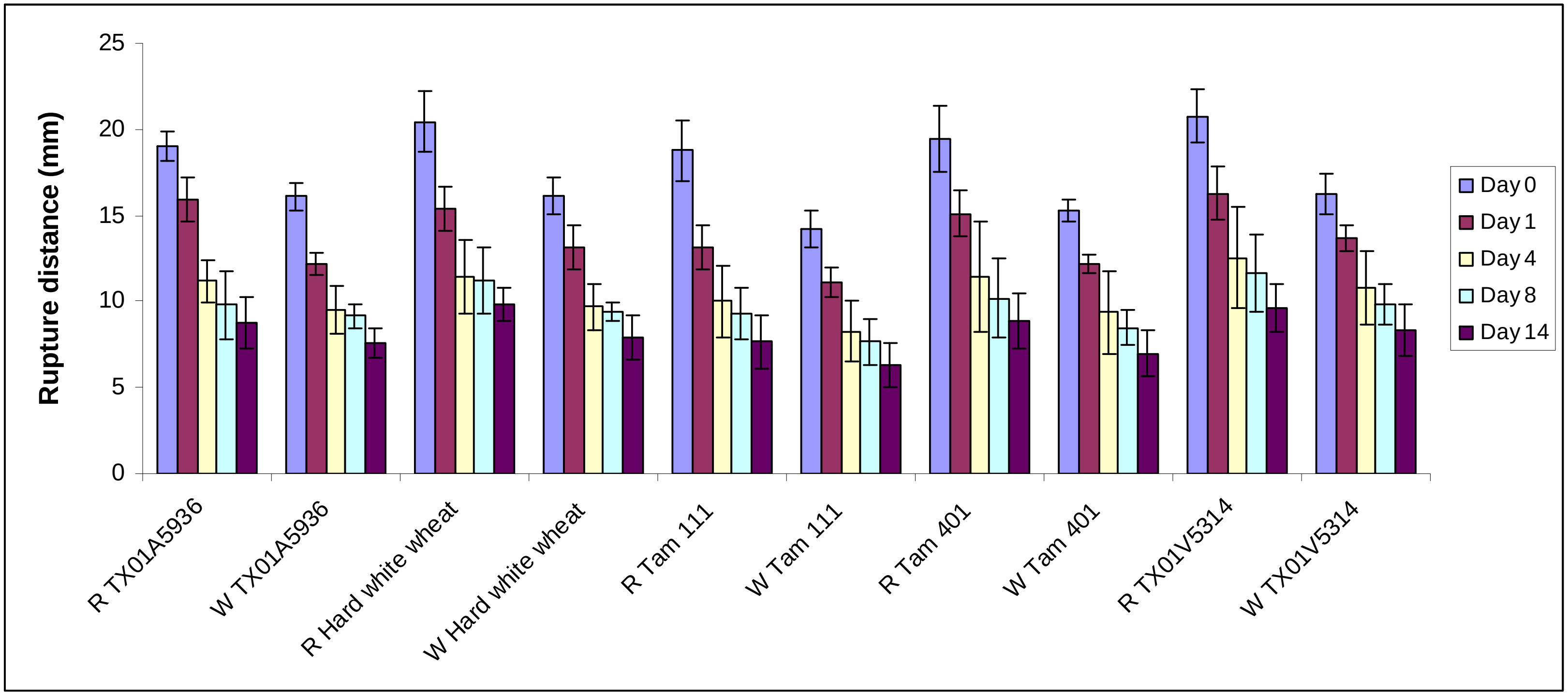


Fig. 25. Effect of storage time on rupture distance (two-dimensional extensibility) of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

Refined flour tortillas had higher rupture distance than whole wheat tortillas over storage time which means that they were more extensible than whole wheat flour tortilla.

Work

For all samples, work decreased over time (Fig. 26). It was not as good as the rupture distance to detect changes in samples during the first 4 days. However, it was sensitive enough to detect changes after 1 day of storage.

In summary, deformation modulus was a good objective parameter to detect textural changes in refined and whole wheat flour tortillas after 4 days of storage whereas the rupture distance parameter was very sensitive to textural changes at the first 4 days of storage.

One-dimensional extensibility

Deformation modulus

Deformation modulus increased over time as observed with the two-dimensional extensibility test (Fig 27). It did not detect changes in tortilla texture between 0 and 1 day of baking. The overall variability of the deformation modulus in 2-D extensibility was higher for refined flour tortilla than whole wheat tortilla (CV=25% and 18%, respectively). For the 1-D extensibility, this variability was higher for whole wheat tortilla than refined flour tortilla (CV= 20% and 33.2%, respectively).

Maximum force

It was not a good parameter to characterize and explain changes in refined wheat flour tortillas and whole wheat flour tortillas over storage time as observed in the two-dimensional extensibility test (Fig. 28).

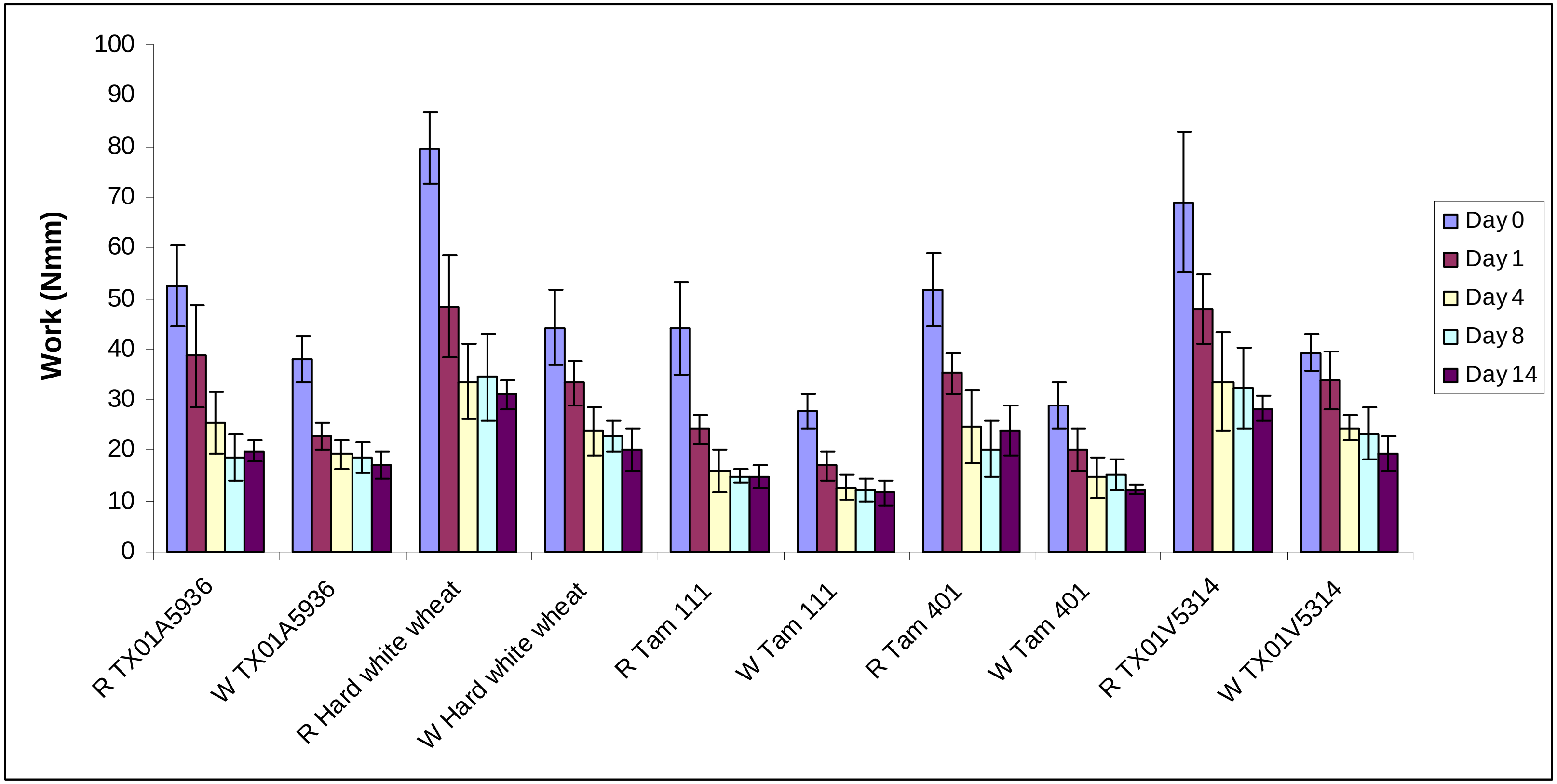


Fig. 26. Effect of storage time on work (two-dimensional extensibility) of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

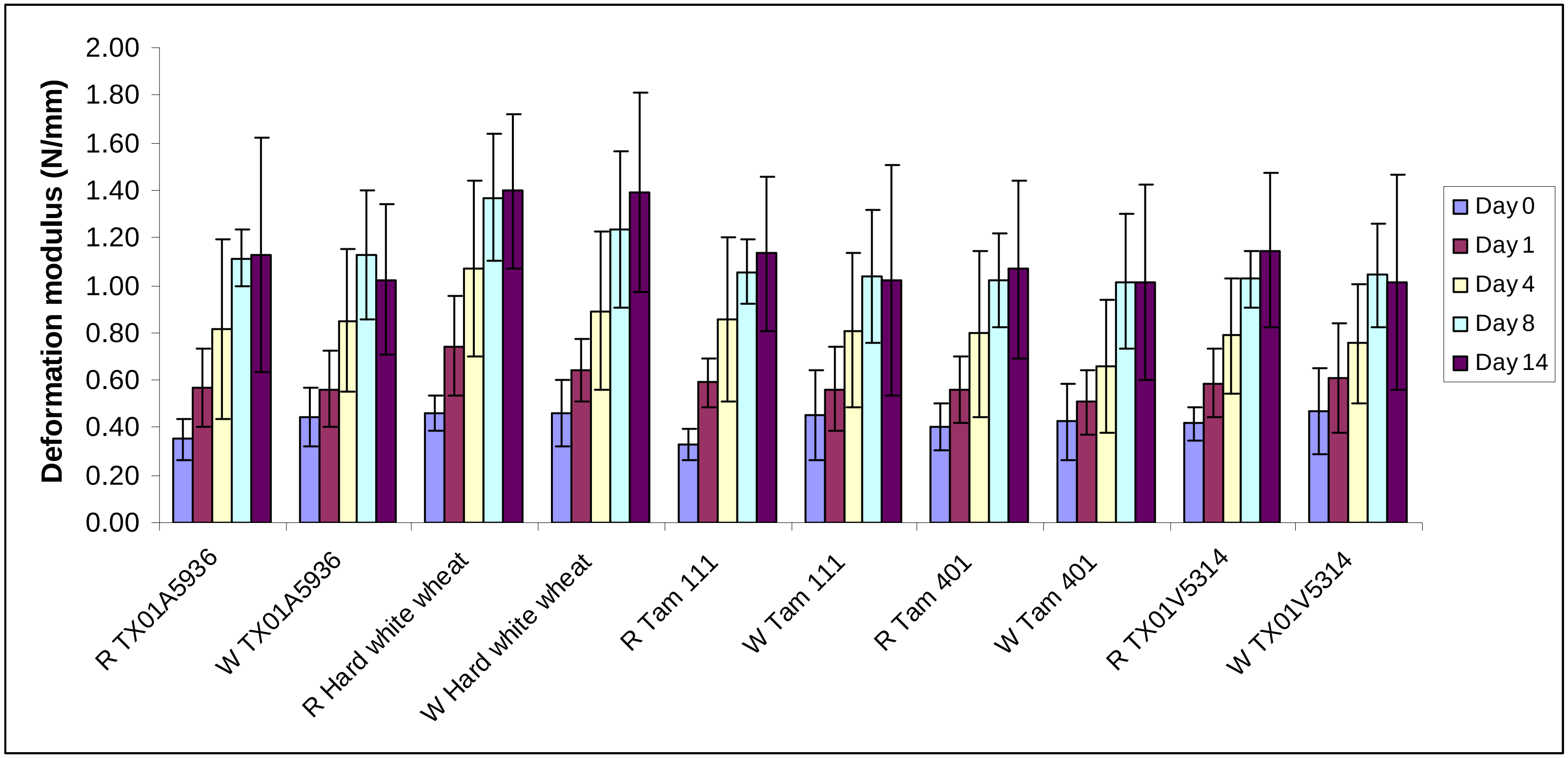


Fig. 27. Effect of storage time on deformation modulus (one-dimensional extensibility) of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

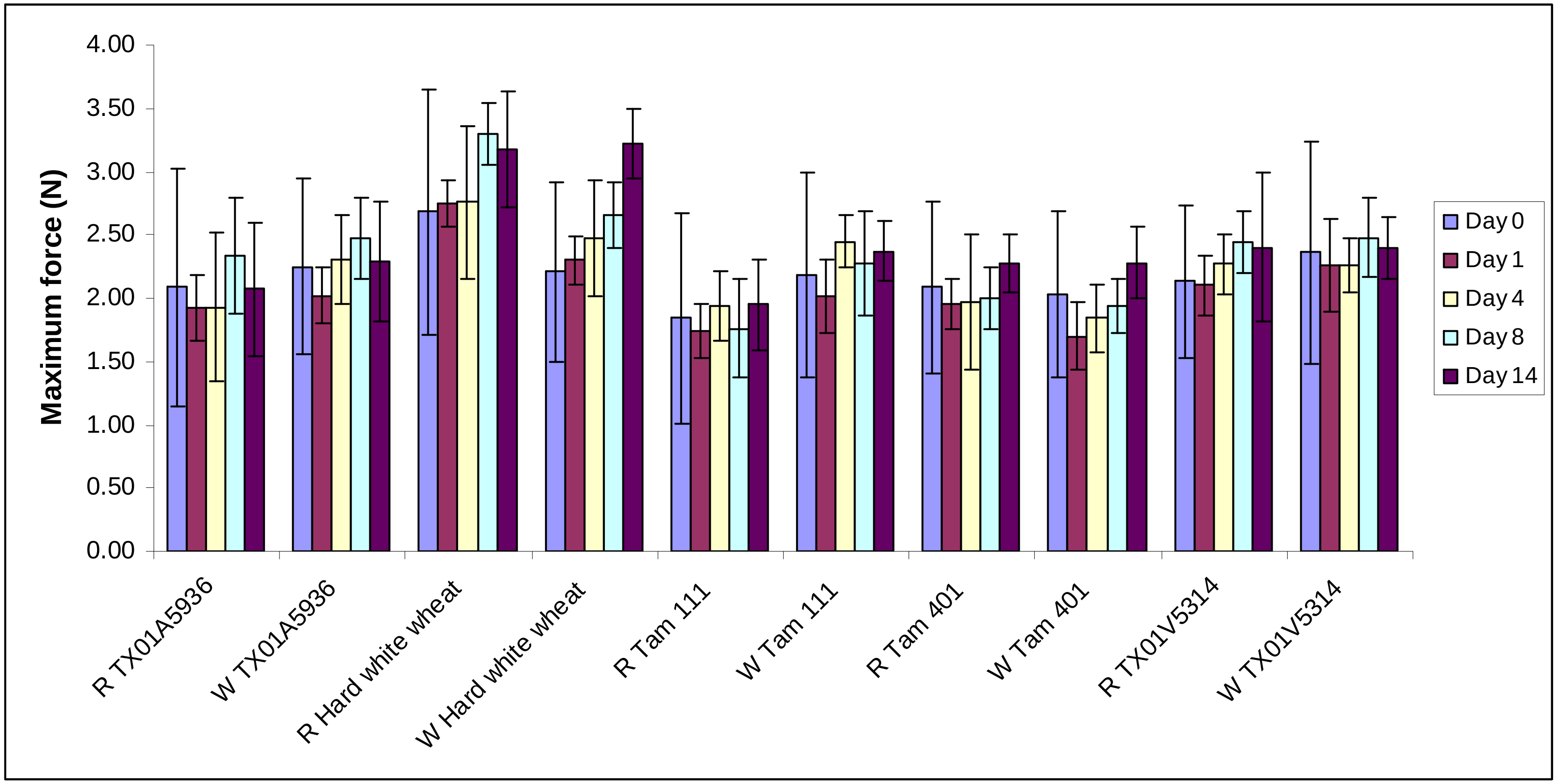


Fig. 28. Effect of storage time on maximum force (one-dimensional extensibility) of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

Rupture distance

For all samples, rupture distance decreased over time (Fig 29). The rupture distance was able to detect differences in the tortilla texture within 4 days of storage and was constant after day 8 as observed in the two-dimensional extensibility test. It was significant and sensitive even after 1 day of storage. Similar results were obtained in the 2-D extensibility test. This is an objective parameter that can be used to study changes in tortillas at the beginning of storage.

The overall variability of the rupture distance in 2-D extensibility was higher for refined flour tortilla than whole wheat tortilla (CV=14.4% and 11.9%, respectively). For the 1-D extensibility, this variability was also higher for refined flour tortilla than whole flour tortilla (CV= 18.7% and 14.6%, respectively). Rupture distance of both techniques is useful to measure changes in tortilla texture within 4 days of storage.

It showed that 1D- extensibility explained changes in tortilla over time as good as 2D- extensibility when deformation modulus and rupture distance were used. Rupture distance can be used to indicate changes within 4 days of storage whereas deformation modulus and subjective rollability can be used to explain textural changes after 4 days of storage. At the end of storage time, deformation modulus does not indicate any change in tortilla texture while subjective rollability is still sensitive.

Moreover, the strong gluten wheat flours, hard white wheat and TX01V5314 presented higher rupture distance values for both refined and whole wheat flour tortillas over storage time meaning they were more extensible, produced better tortillas than the others, correlating with subjective rollability test.

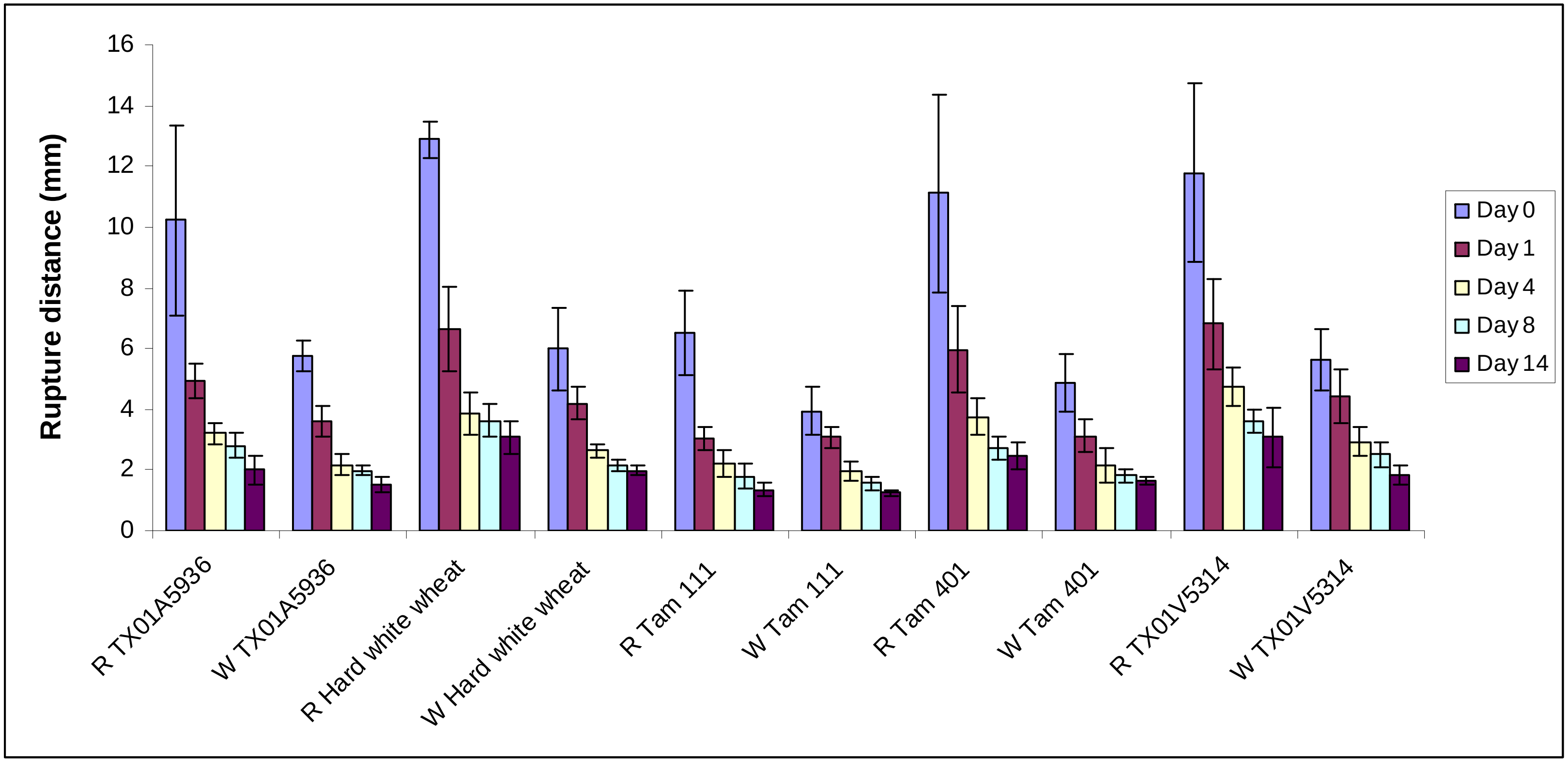


Fig. 29. Effect of storage time on rupture distance (one-dimensional extensibility) of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

1D- extensibility technique is a simple, fast, and repeatable technique for tortilla texture evaluation. Typical one-dimensional extensibility curves obtained from fresh (day 0) and stale (day 14) wheat flour tortillas are shown is Fig. 30.

Stress relaxation

Percent stress relaxation was calculated by dividing the stress at 150 sec to the maximum force for each sample. It was not a good parameter to characterize and explain changes in refined wheat flour tortillas and whole wheat flour tortillas over storage time (Fig. 31).

This was a good parameter used by Singh et al (2006) to compare the rheology of several products such as mozzarella and cheddar cheese, tofu and sausage. However, it was not useful to detect textural changes in tortillas.

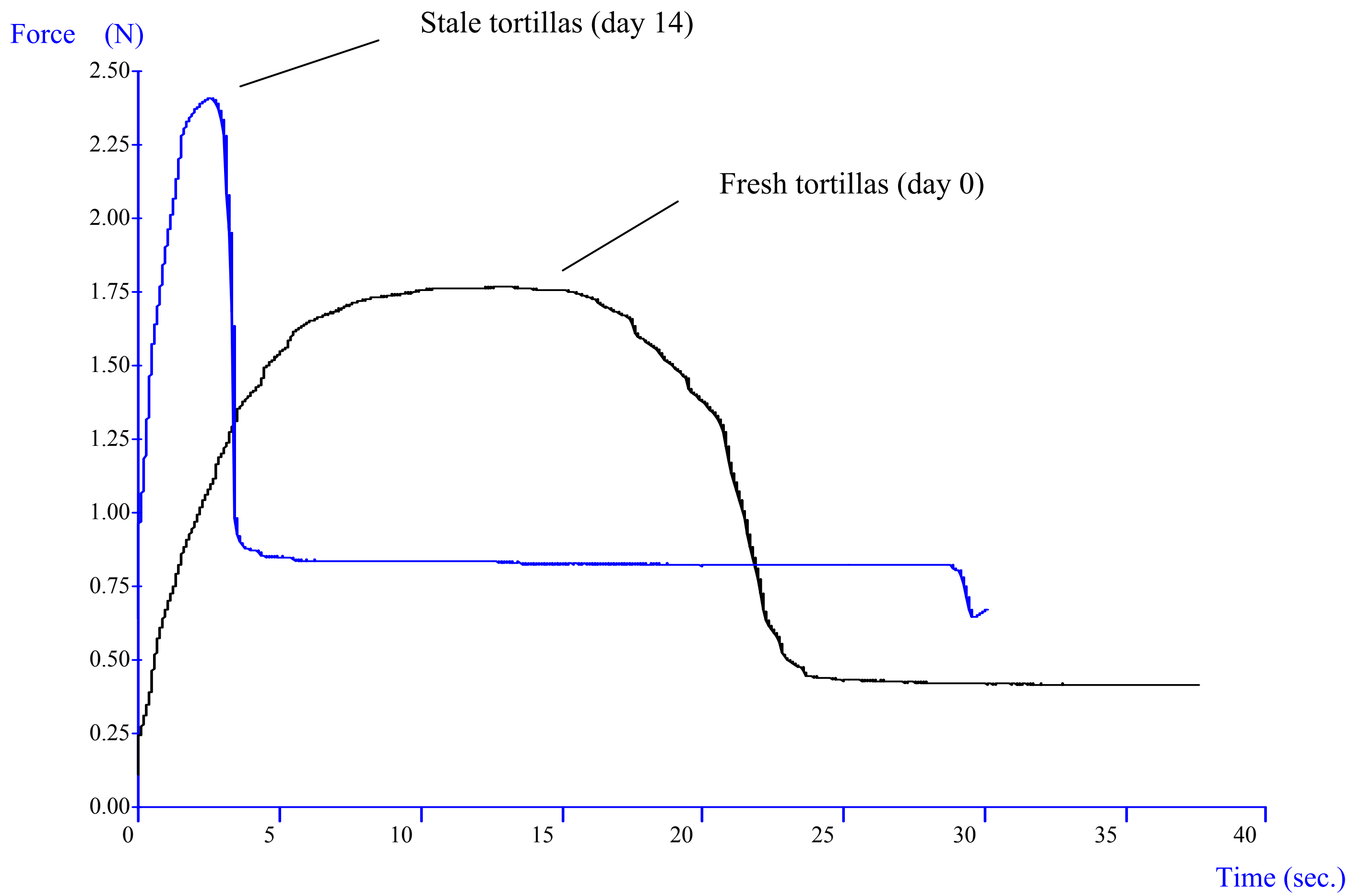


Fig. 30. Typical one-dimensional extensibility behavior from fresh (day 0) and stale (day 14) observed in both refined and whole wheat flour tortillas.

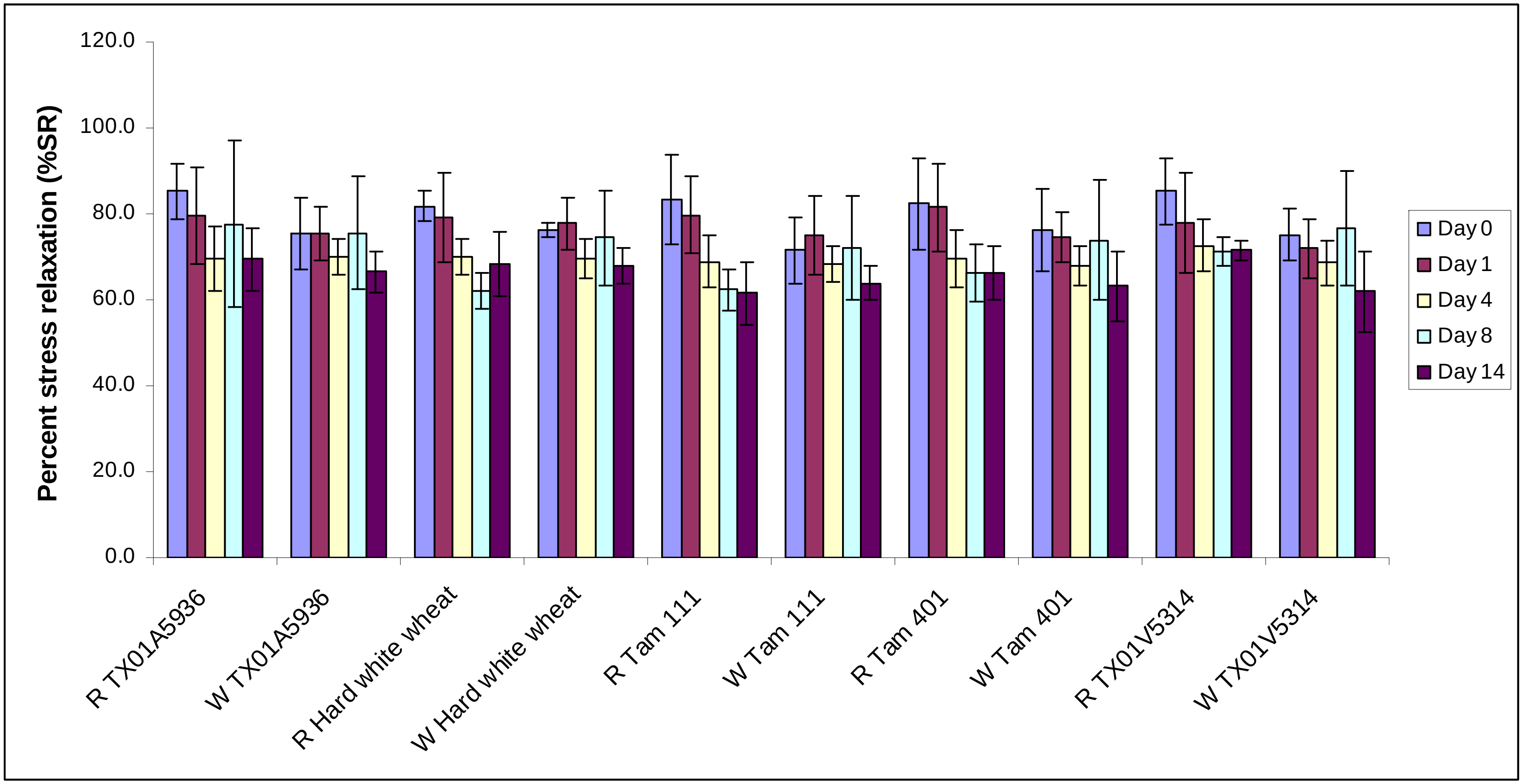


Fig. 31. Effect of storage time on percentage stress (stress relaxation) of refined and whole wheat flour tortillas

R- Refined flour W- Whole wheat flour

CHAPTER V

SUMMARY AND CONCLUSIONS

Tortilla quality was explained best by extensibility than mixing parameters, as analyzed with simple correlation coefficients and multi-linear regression. It was also better than grain-flour chemical analysis and compression tests.

Gluten index provided the highest correlation between a grain-flour chemical parameter and tortilla quality. It was highly negatively correlated with tortilla diameter ($r = -0.67$, $P<0.01$) and specific volume ($r = -0.73$, $P<0.01$). Protein content significantly correlated ($P<0.05$) with tortilla diameter ($r= -0.52$), maximum force ($r= 0.53$) and work ($r= 0.57$).

Among the rheological tests, dough resistance to extension, ratio of dough resistance to extension-extensibility, farinograph and mixograph parameters were correlated with tortilla quality parameters. Dough resistance to extension was the parameter which correlated the best with tortilla quality. Diameter, specific volume, deformation modulus, maximum force and work were highly correlated with dough resistance to extension ($r= -0.87$, -0.85, 0.71, 0.86, 0.69, respectively, $P<0.01$). Resistance to extension was also used to compare strength (elasticity) of dough and gluten. Gluten had significantly higher resistance to extension than dough.

Stepwise multiple regression models helped explain tortilla quality. After validation analysis, tortilla diameter was the quality parameter best predicted ($r^2 = 0.87$)

by mix-time and dough resistance to extension. The rheological tests provided the best prediction models.

Refined flour dough had higher extensibility than whole wheat flour dough. Whole wheat flour tortillas were larger, thinner and less opaque than refined flour tortillas. The refined flour had particle size equal or smaller than 0.074 mm whereas the whole wheat flour had particle size between 0.25 and 0.42 mm. Dough rheology was affected by the flour type.

Among whole wheat flours, the strong ones gave larger tortillas with longer shelf-stability. One whole white and one whole red wheat produced the best tortillas among the whole wheat flours. Consumers prefer tortillas made with whole white wheat.

Different rheological techniques were used to characterize the texture of refined and whole flour tortillas during storage. Among the objective rheological techniques, rupture distance from 1-D and 2-D extensibility tests was the best parameter to detect textural changes in tortillas from 0 to 4 days of storage. Deformation modulus, from the same techniques, and subjective rollability method were good parameters to detect change in tortillas after 4 days of storage. However, at the end of storage the subjective rollability test was the only one able to identify textural changes such as flexibility.

SUGGESTIONS FOR FURTHER RESEARCH

In this study, large amount of wheat flour and tortilla ingredients were used to prepare dough samples and tortillas for all tests done. Dough resistance to extension was the best predictor of tortilla quality. The extensibility test requires small amounts of flour which is an advantage for wheat quality selection. Therefore, in the future, extensibility test could be done using small amount of flour and new correlation and prediction models could be developed.

Subjective rollability was not included as a dependent variable in this research because of mold contamination, which reduced the storage time to 12 days. Thus, it was not possible to see differences among samples. For the future, tortilla texture should be studied for at least 16 days, and prediction models for rollability should be developed. Refrigeration can also be used

More wheat samples should be used to validate the prediction models obtained in this research. Moreover, new models using different software and techniques should be developed. All these will help to improve the data obtained in this research.

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APPENDIX A

TYPICAL GRAPHS FOR THE OBJECTIVE RHEOLOGICAL METHODS

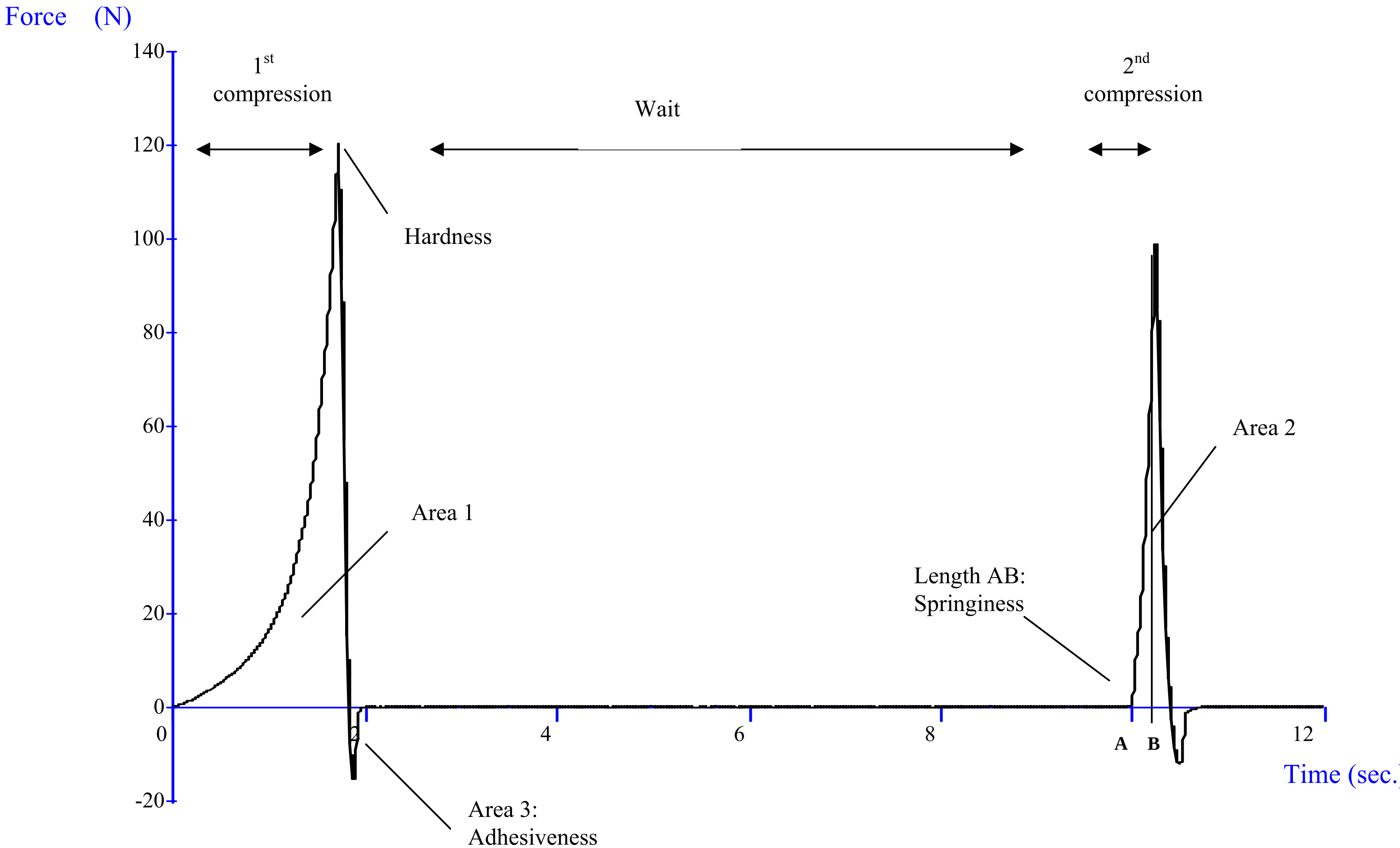

Fig. A1. Typical graph for Texture profile analysis (TPA) of wheat dough

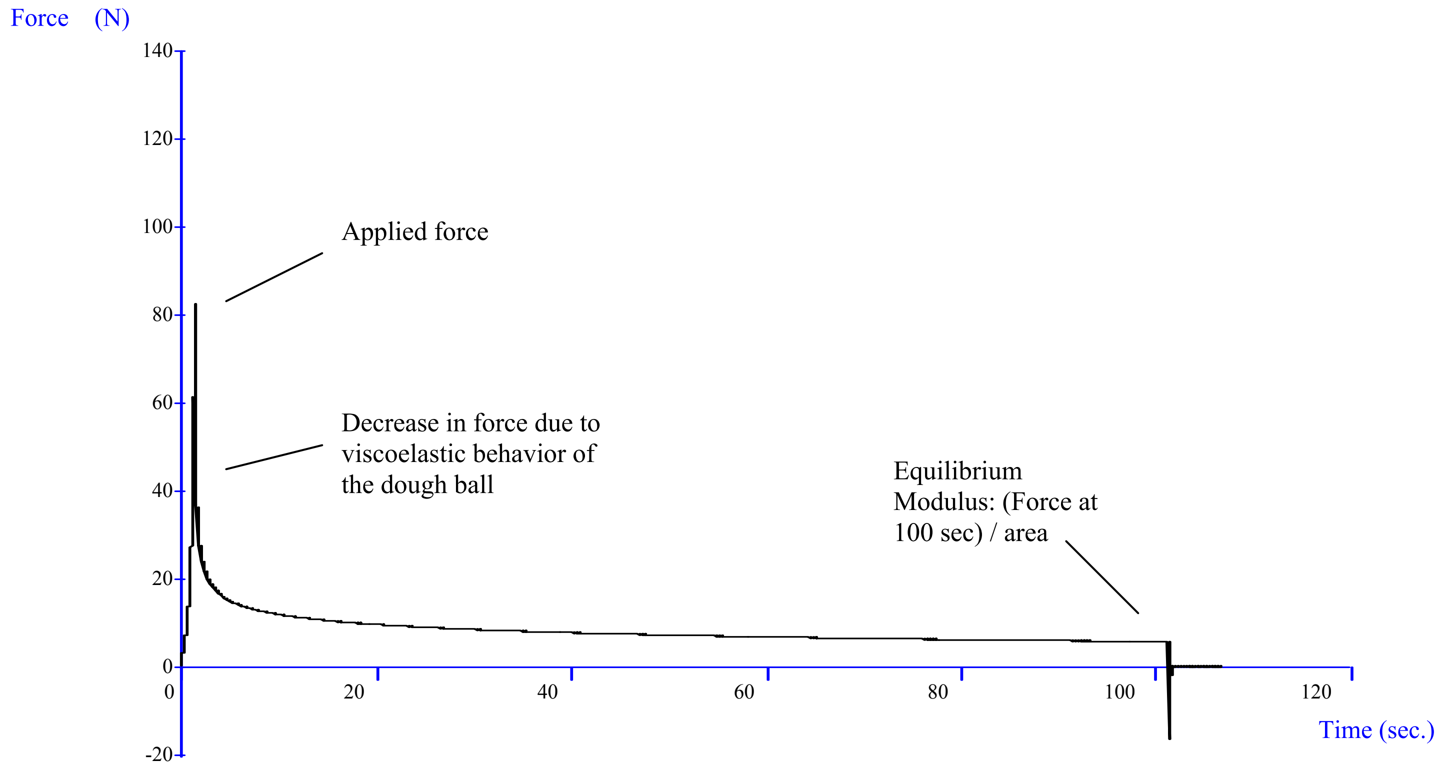

Fig. A2. Typical graph for stress relaxation raw data.

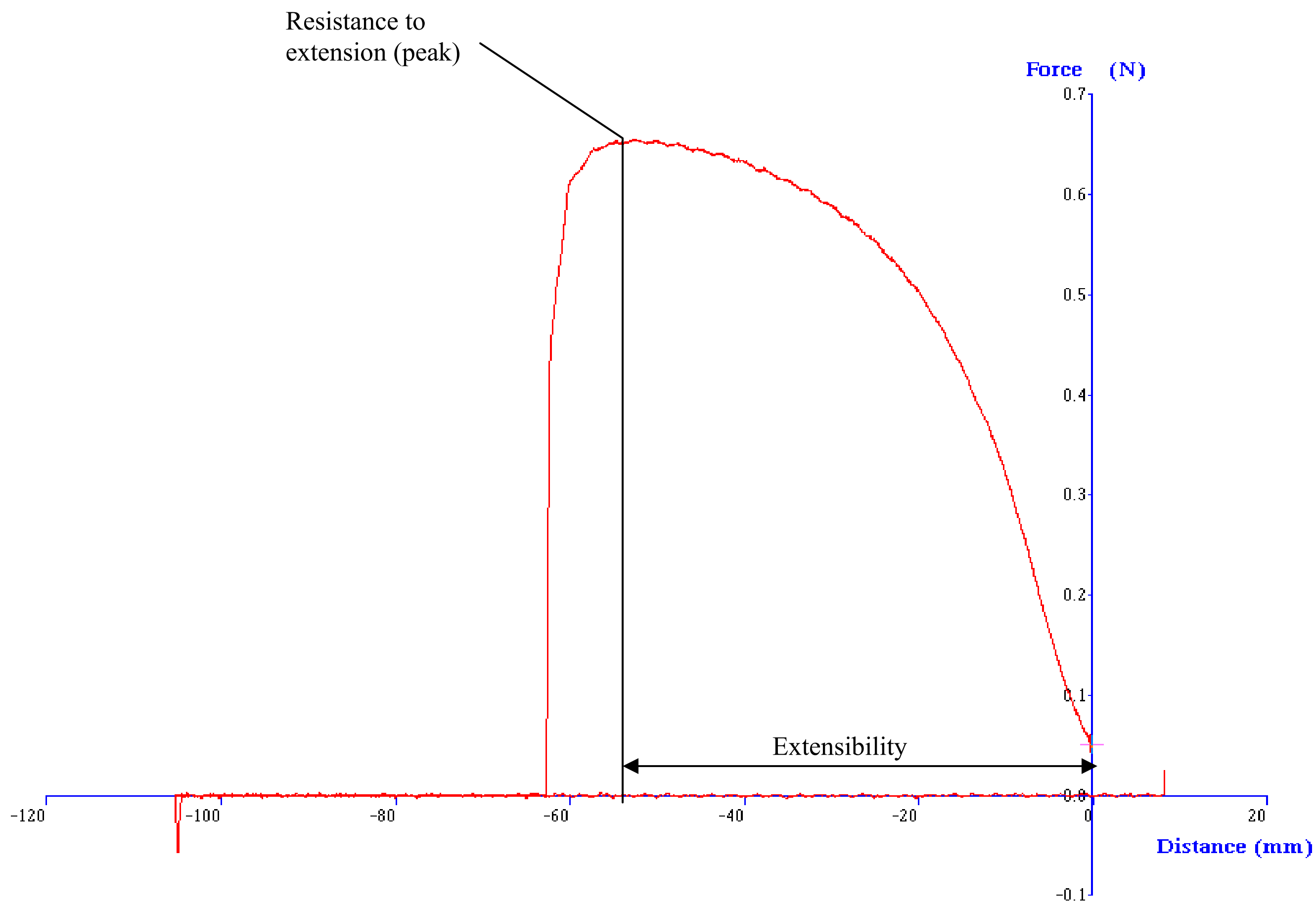

Fig. A3. Typical graph for dough and gluten extensibility test.

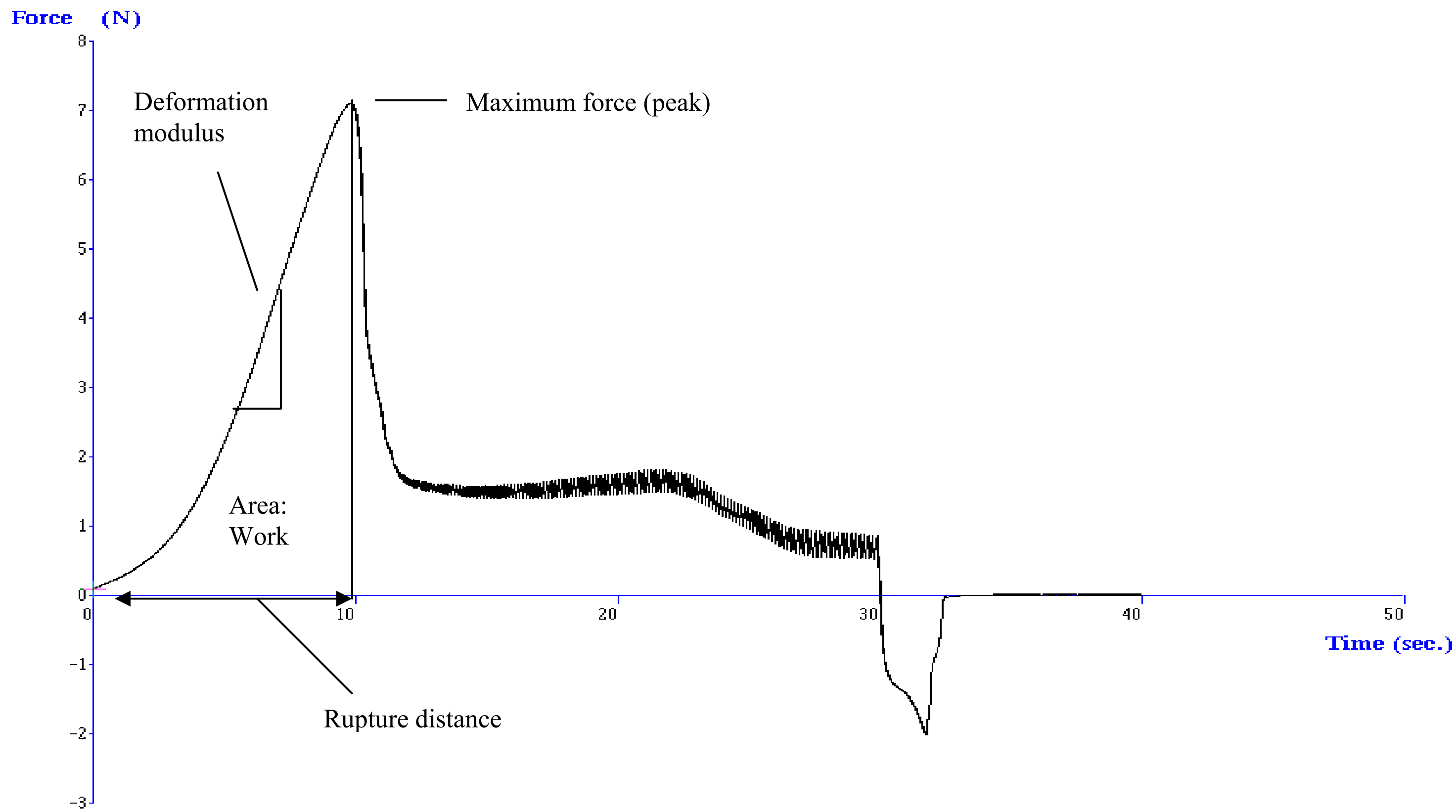

Fig. A4. Typical graph for tortilla two-dimensional extensibility test.

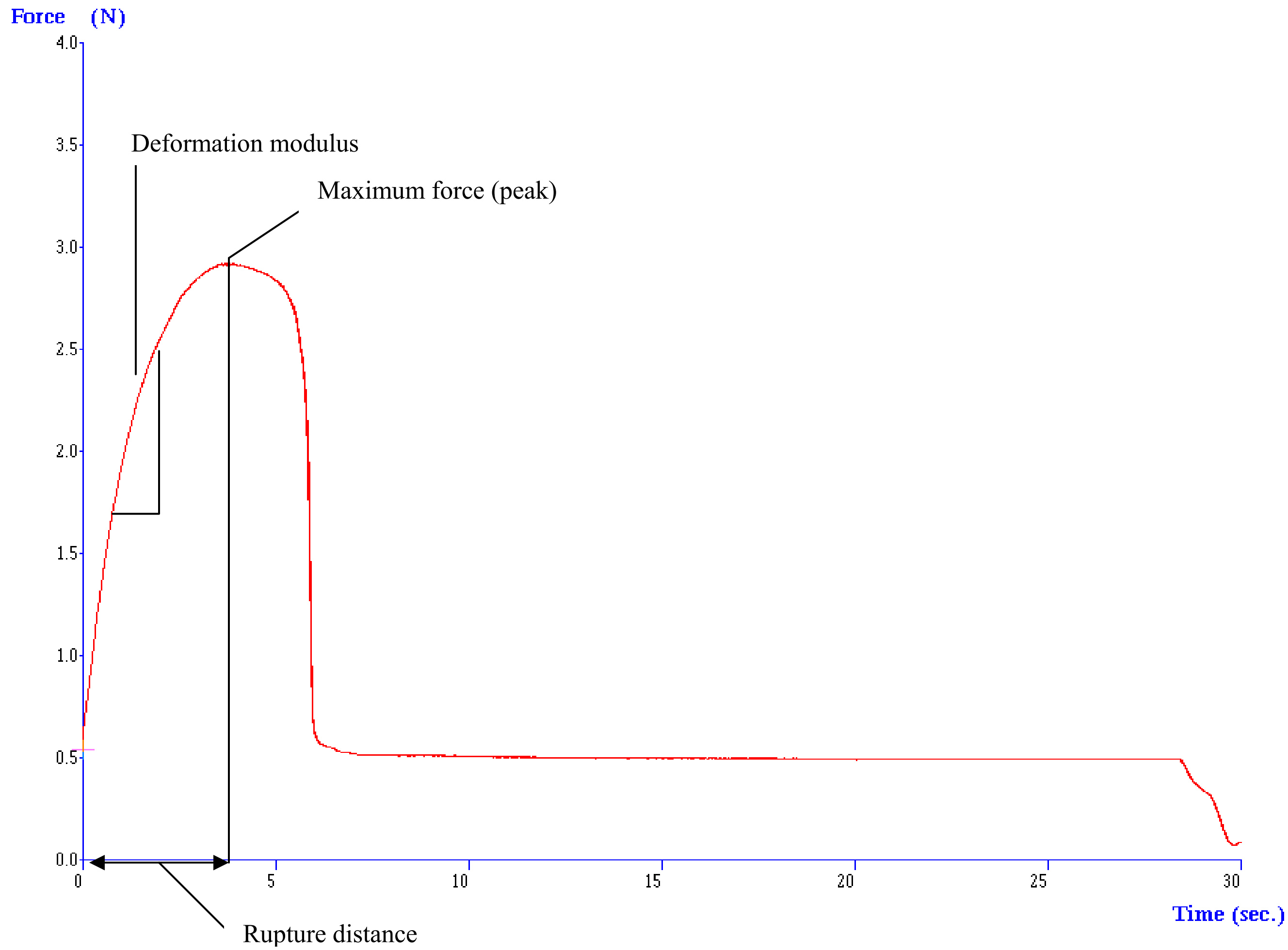

Fig.A5. Typical graph for the tortilla one-dimensional extensibility test

APPENDIX B

PRELIMINARY TESTS

MATERIALS AND METHODS

Effect of the amount of water on dough rheology

Refined malted wheat flour (ADM Milling Co., Overland Park, KS) and whole white wheat flour (Farmer Direct Foods, Atchison, KS) were used to determine the effect of moisture on dough rheology.

The following ingredients were used: 500 g flour and 7.5 g salt (Morton International, Inc., Chicago, IL). Different amount of distilled water was used. For the refined flour, 260, 280 and 300 g were used. For whole wheat flour, the amount of water was 270, 300 and 310 g.

Texture analyzer was used to obtain and record dough hardness (N) from Texture Profile Analysis (TPA) tests (the TPA set cited before was used, but the strain used for this specific test was 75% instead of 70%), and equilibrium force (N) using the Stress Relaxation method.

Effect of tortilla ingredients on dough rheology

Refined malted wheat flour (ADM Milling Co., Overland Park, KS), unbleached all purpose flour (10% protein, Hodgson Mill, Inc., Effingham, IL), unbleached bread flour (13.3% protein, The King Arthur Flour Company, Inc., Norwich, Vermont) and whole white wheat flour (Farmer Direct Foods, Atchison, KS) were used to compare dough rheological properties with and without (only flour, salt and water) tortilla ingredients.

The following ingredients were used: 500 g wheat flour, 30 g shortening (Sysco Corp., Houston, TX), 7.5 g salt (Morton International, Inc., Chicago, IL), 3 g sodium bicarbonate (Arm and Hammer, Church and Dwight Company, Inc, Princeton, NJ), 2.9 g sodium aluminum sulfate (Budenheim USA, Inc, Plainview, NY), 2.5 g sodium steroyl lactylate (Caravan Ingredients, Lenexa, KS), 2 g sodium propionate (Niacet Corp., Niagara Falls, NY), 2 g potassium sorbate (B.C.Williams, Dallas, TX), 1.65 g encapsulated fumaric acid (Balchem Corp., New Hampton, NY), 0.015 g cysteine (Fleishmann's yeast, Inc., Burr Ridge, IL). The amount of distilled water was 260 g to control and All purpose and 270 g for bread flour and whole wheat flour.

The TA.XT2i Texture Analyzer was used to obtain objective data from TPA, equilibrium force (N) from the Stress Relaxation method, resistance to extension (N) and extensibility (mm) using the Kieffer Dough & Gluten Extensibility Rig.

RESULTS AND DISCUSSION

Effect of the amount of water on dough rheology

As the amount of added water increased, the hardness of both refined and whole wheat dough decreased (Fig.B1). It showed that a very simple test such as hardness was sensitive enough to differentiate doughs with different amount of water. Equilibrium modulus (stress relaxation test) also differentiates the samples (Fig.B2) but it was not as sensitive as hardness from the TPA test.

This test was conducted to observe whether or not water absorption affects dough rheology. Excess of water was not used. The amount of water added ranged from the one used to make tortillas and 2% less of the one necessary to make the dough sticky. Water absorption was really important in order to evaluate compression tests on dough.

Effect of tortilla ingredients on dough rheology

TPA test

The same behavior was observed for hardness, cohesiveness and adhesiveness among the samples (Fig B3, B4 and B5). Addition of tortilla ingredients decreased the values of these variables for all purpose flour and whole wheat flour doughs. For springiness, only all purpose flour was affected by addition of ingredients (Fig. B6). The add of ingredients, especially shortening; make the dough to be softer and this results in less firmness, hardness.

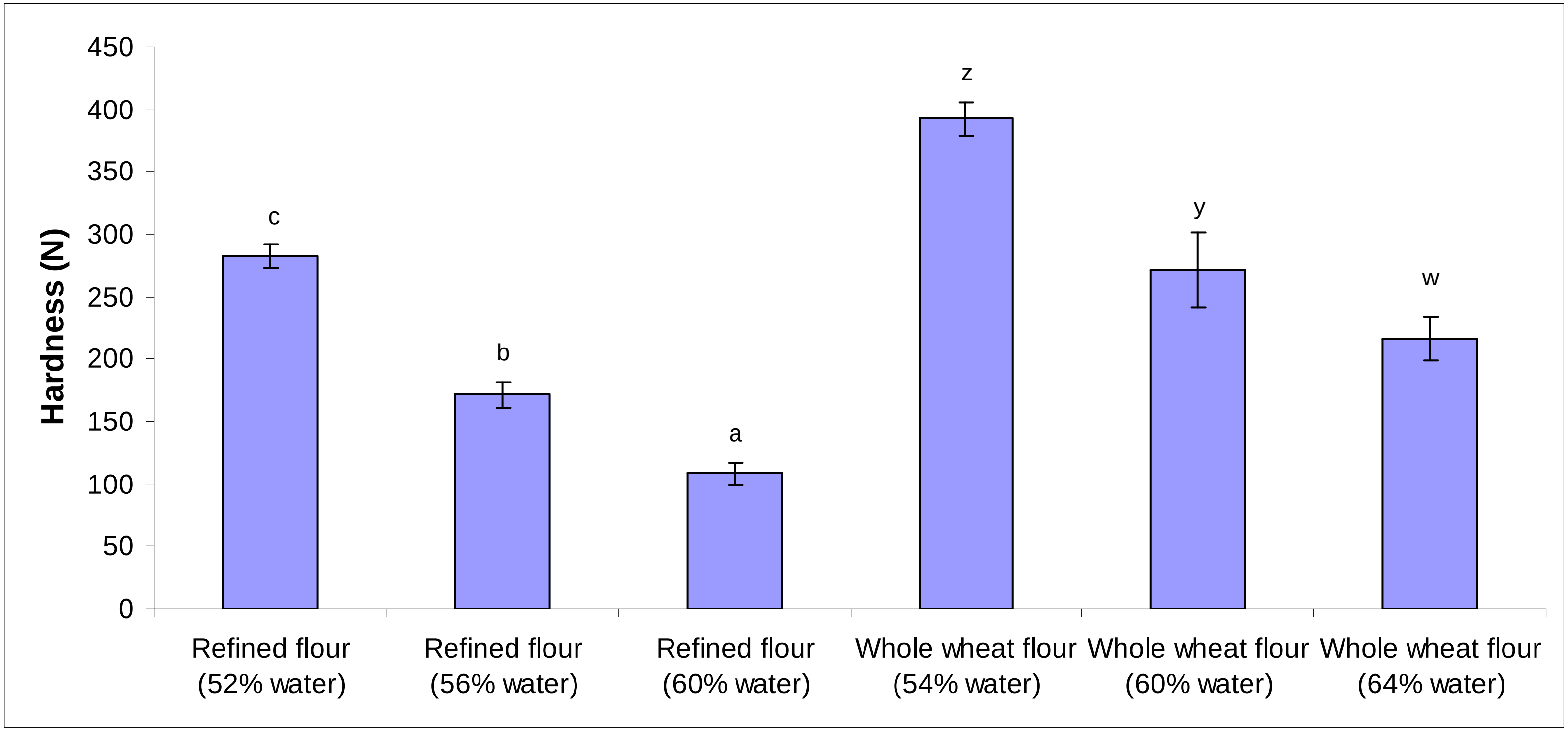

Fig. B1. Hardness of dough samples produced with different amount of water.

Values with the same letter for each sample are not significantly different (P≤ 0.05).

Fig. B2. Stress relaxation test for dough samples produced with different amount of water. Values with the same letter for each flour are not significantly different ($P \leq 0.05$).

Fig. B3. Hardness (TPA test) of dough samples made with and without tortilla ingredients.

Values with the same letter for each flour are not significantly different (P≤ 0.05).

Fig. B4. Cohesiveness (TPA test) of dough samples made with and without tortilla ingredients.

Values with the same letter for each flour are not significantly different (P≤ 0.05).

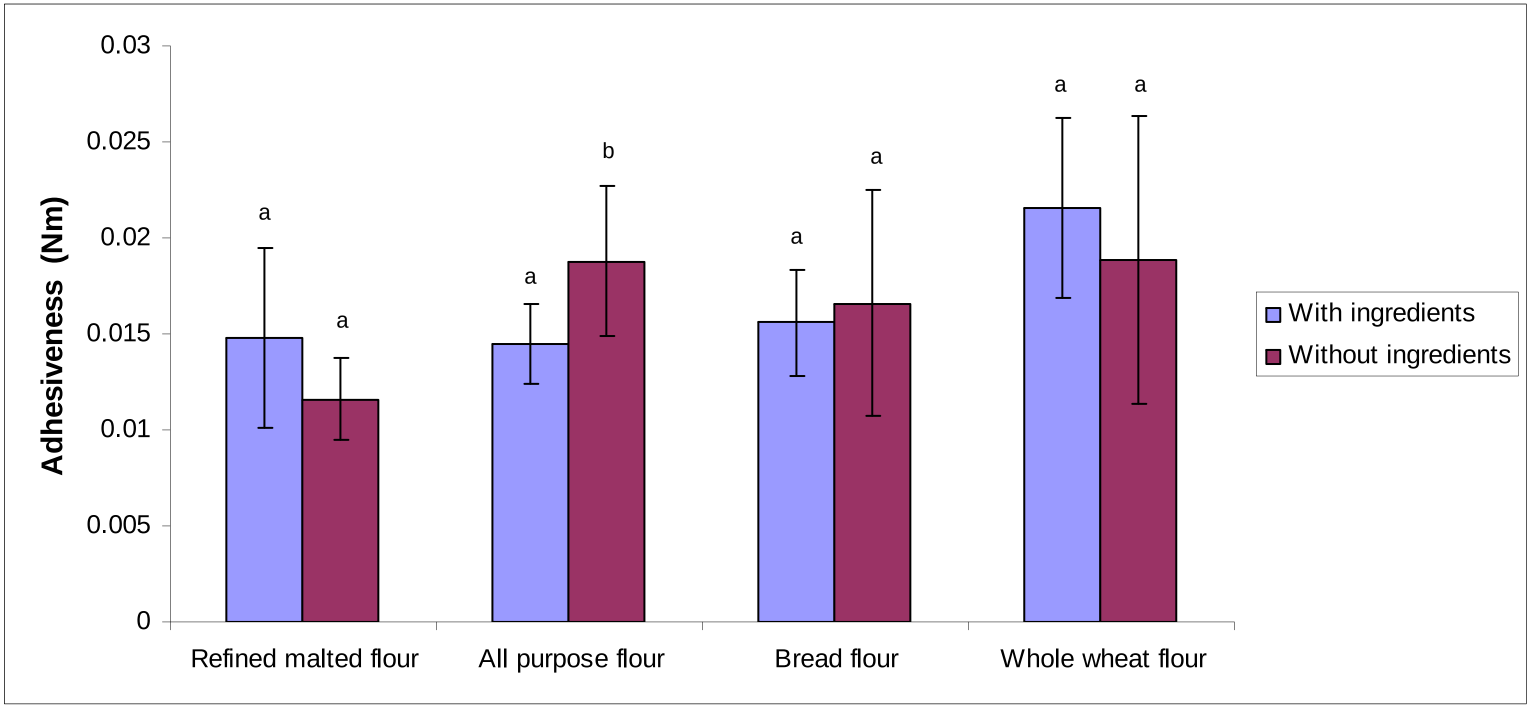

Fig. B5. Adhesiveness (TPA test) of dough samples made with and without tortilla ingredients.

Values with the same letter for each flour are not significantly different (P≤ 0.05).

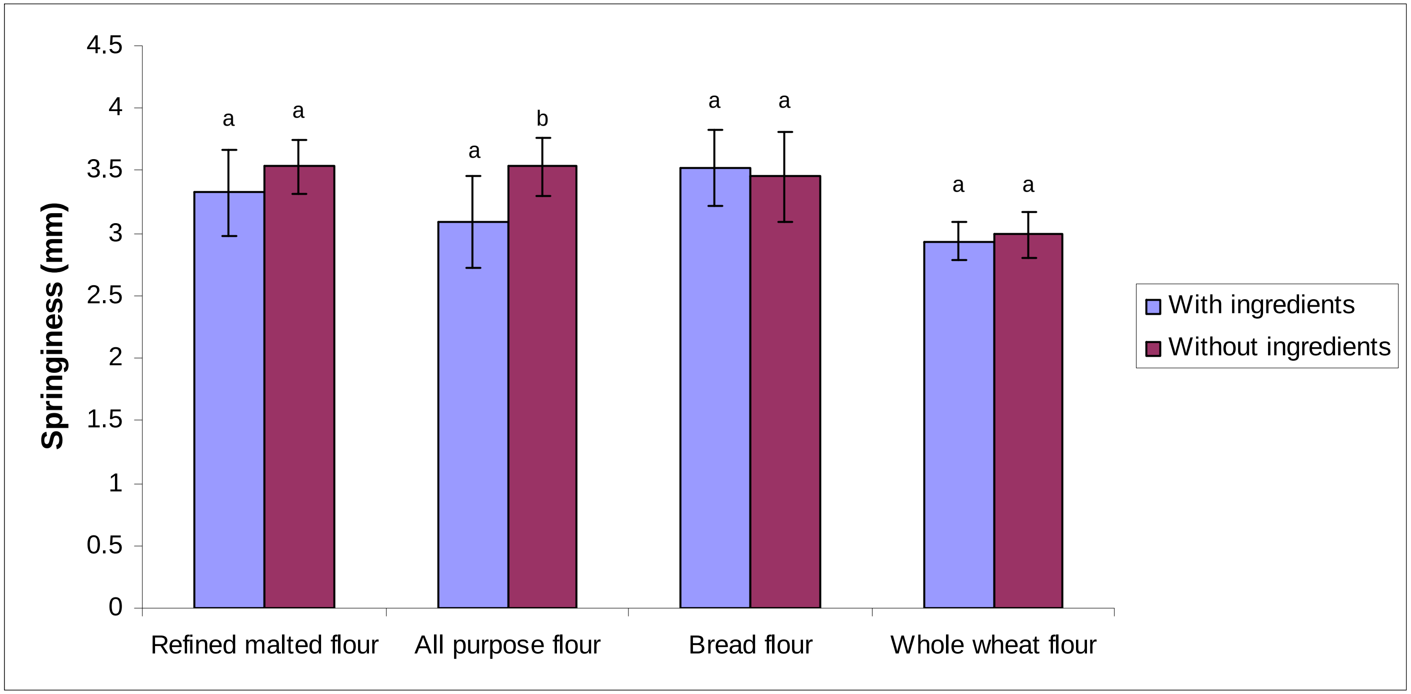

Fig. B6. Springiness (TPA test) of dough samples made with and without tortilla ingredients.

Values with the same letter for each flour are not significantly different ($P \leq 0.05$).

Stress relaxation test

Equilibrium modulus was higher for the wheat flour doughs with tortilla ingredients than for those without ingredients (Fig.B7). The higher the equilibrium modulus the stronger, more elastic the dough structure is. This means that tortilla ingredients help somehow in the gluten structure, softening the dough and increasing its strength.

Extensibility test

Resistance to extension and extensibility differed depending on the sample (Appendix, Fig.B8 and B9). Addition of ingredients did not affect the values.

It was not possible to conclude whether or not tortilla ingredients affect dough rheology, because there was no consistent behavior among the samples. Only stress relaxation test provided consistent results.

In this study, tortilla ingredients were added to make tortilla dough. By doing that, we hoped for improved correlation. Tests using only flour, water and salt can be done in the future to save time and samples since tortilla ingredients did not affect dough rheology.

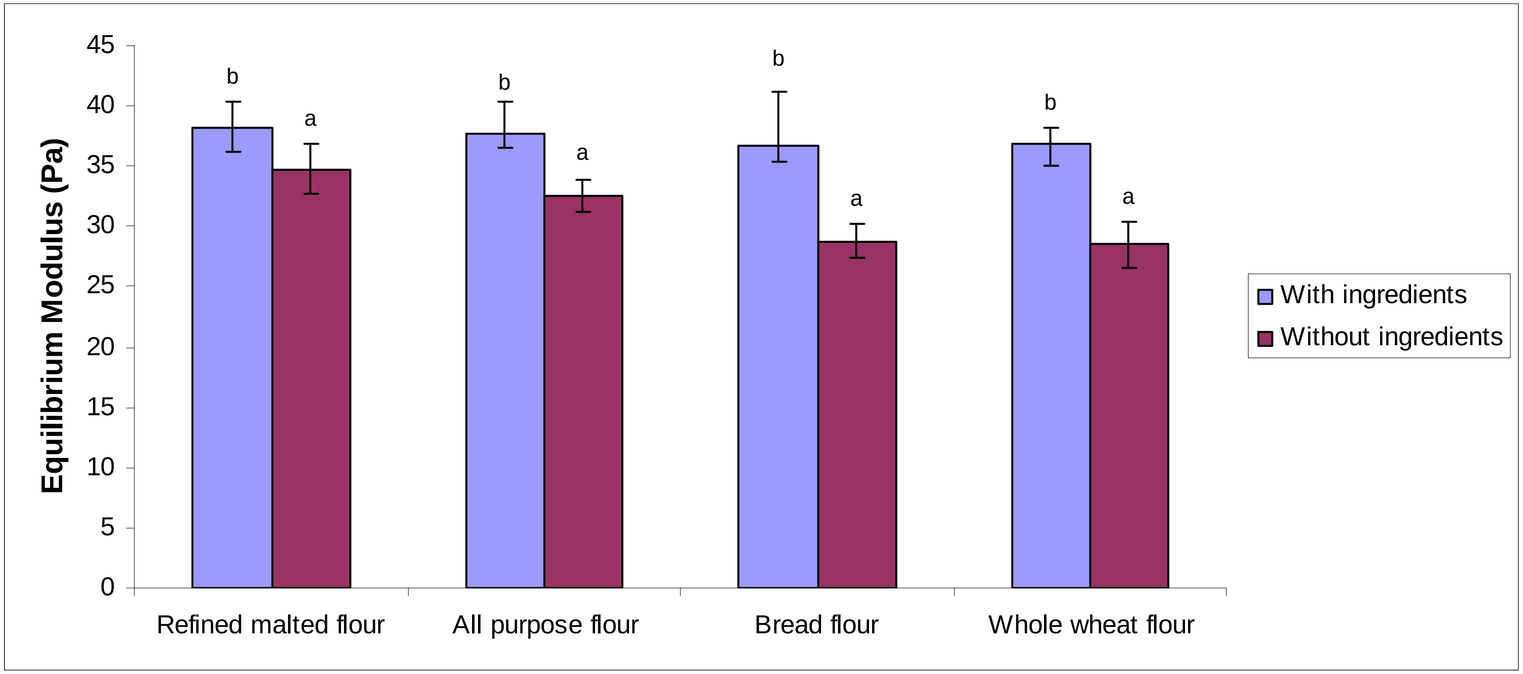

Fig. B7. Equilibrium modulus (Stress relaxation test) of dough samples made with and without tortilla ingredients

Values with the same letter for each flour are not significantly different (P≤ 0.05).

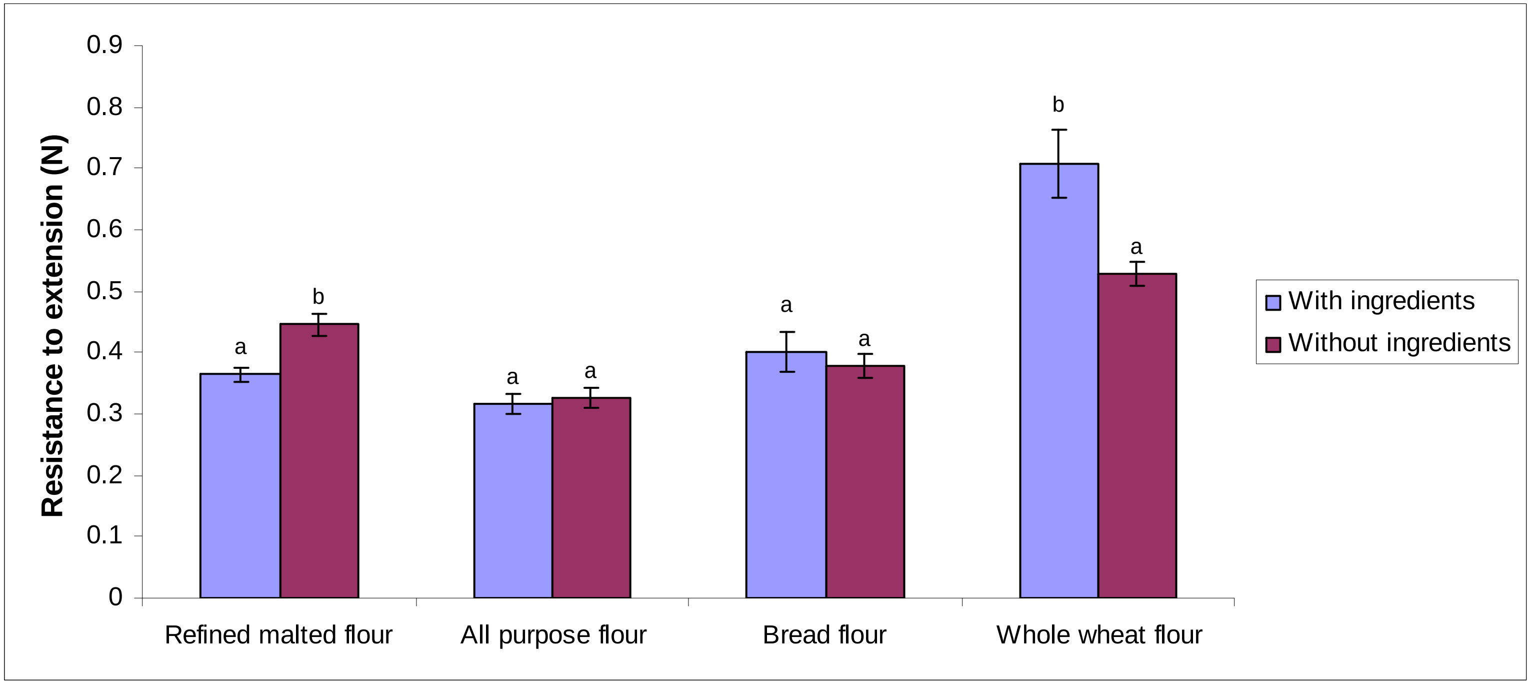

Fig. B8. Resistance to extension (extensibility test) of dough samples made with and without tortilla ingredients

Values with the same letter for each flour are not significantly different (P≤ 0.05).

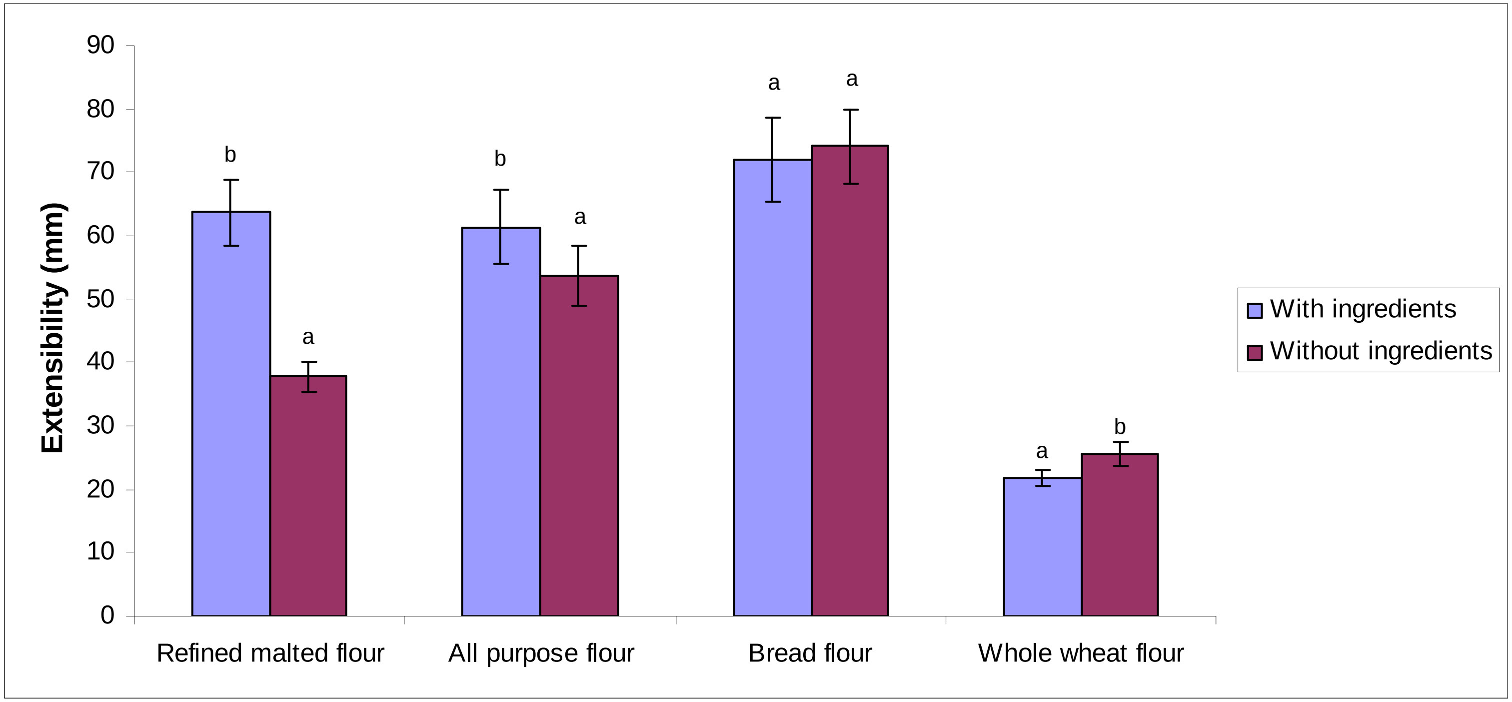

Fig. B9. Extensibility (extensibility test) of dough samples made with and without tortilla ingredients

Values with the same letter for each flour are not significantly different (P≤ 0.05).

APPENDIX C

DATA TABLES AND GRAPHS

TABLE C1
Physico-chemical tests evaluated for the 16 wheat flours*

Flours	**Variables**	
	Sedimentation height (cm)	**True density (g/cm^3)**
1	10.66a ± 0.47	1.46a ± 0.014
2	10.80a ± 0.7	1.47a ± 0.0033
3	11.23a ± 0.48	1.47a ±0.00081
4	10.75a ± 0.42	1.48a ± 0.0012
5	10.75a ± 0.65	1.47a ± 0.0062
6	10.41a ± 0.43	1.49a ± 0.021
7	10.13a ± 0.54	1.46a ± 0.0049
8	10.66a ± 0.54	1.47a ± 0.0052
9	10.77a ± 0.47	1.47a ± 0.0057
10	10.95a ± 0.58	1.47a ± 0.0087
11	10.77a ± 0.79	1.48a ± 0.011
12	10.75a ± 0.39	1.47a ± 0.0051
13	10.67a ± 0.66	1.46a ± 0.0043
14	10.55a ± 0.38	1.46a ± 0.00051
15	10.69a ± 0.49	1.46a ± 0.00069
16	11.19a ± 0.5	1.46a ± 0.0083

*Means followed by the same letter in the same column are not significantly different ($P < 0.05$)

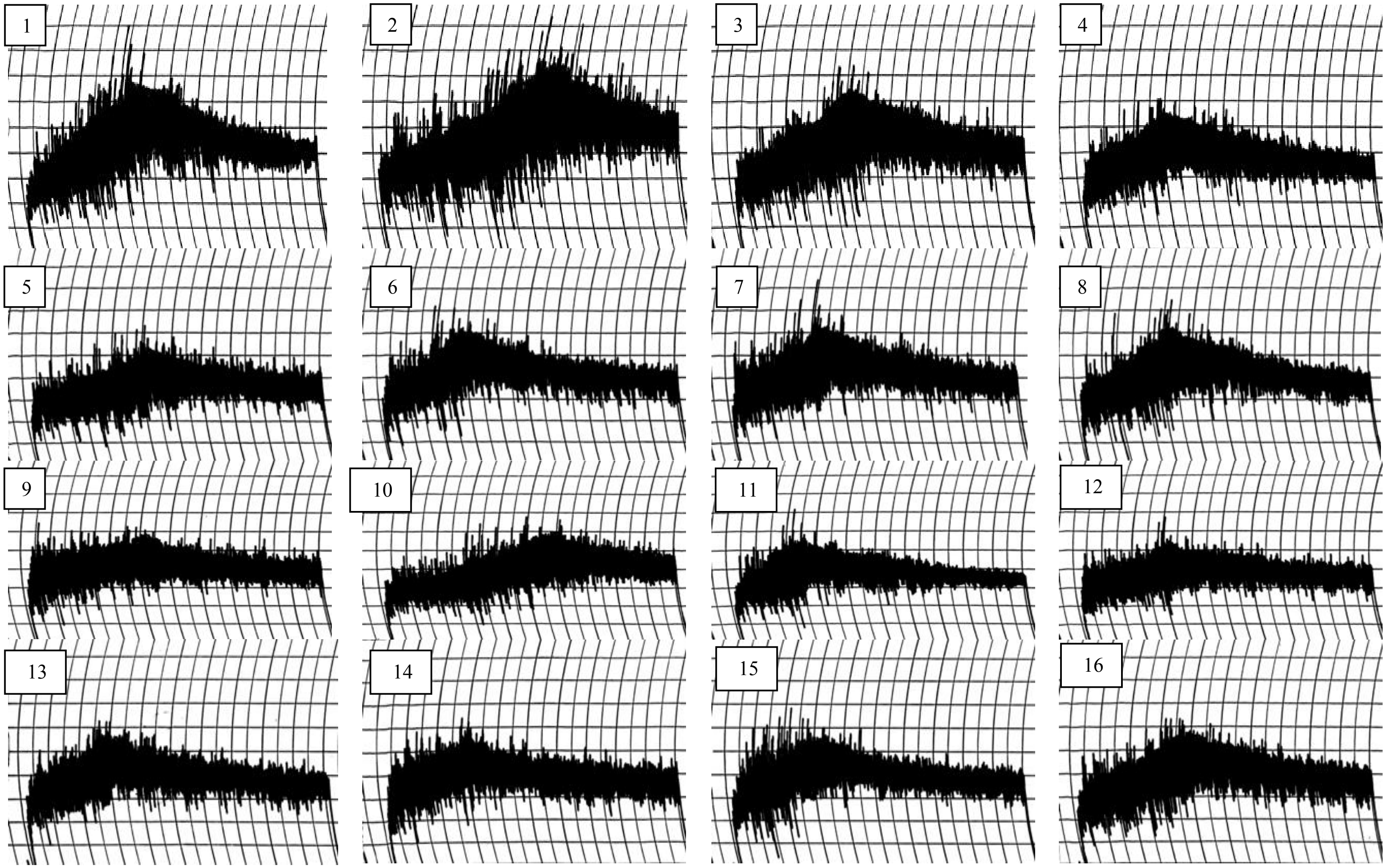

Fig C1: Mixograms of the 16 wheat flours (WQC, 2007)

TABLE C2
Subjective evaluation of dough properties *

Flours	Variables**			
	Smoothness	**Softness**	**Extensibility**	**Force to extend**
1	1.5a ± 0	1.0a ± 0	3.8b ± 0.35	2.8a,b ± 0.35
2	1.5a ± 0	1.5a,b ± 0	3.0a,b ± 0	3.5 ± 0
3	1.5a ± 0	1.5a,b ± 0	3.0a,b ± 0	3.3a,b,c ± 0.35
4	1.5a ± 0	1.8b ± 0.35	3.0a,b ± 0	3.3a,b,c ± 0.35
5	2.0a ± 0	2.3b,c ± 0.35	2.5a ± 0	4.0c ± 0
6	1.5a ± 0	1.5a,b ± 0	3.3a,b ± 0.35	2.5a,b ± 0
7	1.5a ± 0	2.3b,c ± 0.35	3.0a,b ± 0	3.5b,c ± 0
8	1.5a ± 0	2.5c ± 0	3.3a,b ± 0.35	3.5b,c ± 0
9	1.5a ± 0	2.3b,c ± 0.35	3.3a,b ± 0.35	3.5b,c ± 0
10	1.5a ± 0	2.0b,c ± 0	3.3a,b ± 0.35	3.3a,b,c ± 0.35
11	1.5a ± 0	1.8b ± 0.35	3.8b ± 0.35	2.8a,b ± 0.35
12	1.8a ± 0.35	2.0b,c ± 0	3.8b ± 0.35	3.0a,b,c ± 0.7
13	1.5a ± 0	1.5a,b ± 0	4.0b ± 0	3.0a,b,c ± 0
14	1.5a ± 0	1.5a,b ± 0	4.0b ± 0	2.8a,b ± 0.35
15	1.5a ± 0	1.5a,b ± 0	4.0b ± 0	2.8a,b ± 0.35
16	1.8a ± 0.35	2.0b,c ± 0	3.3a,b ± 0.35	2.3a ± 0.35

* Means followed by the same letter in the same column are not significantly different ($P \leq 0.05$)

** Softness: 1 – very soft, 5 – firm; Extensibility: 1 – not extensible, 5 – very extensible; Force to extend: 1 – less force, 5 – much force.

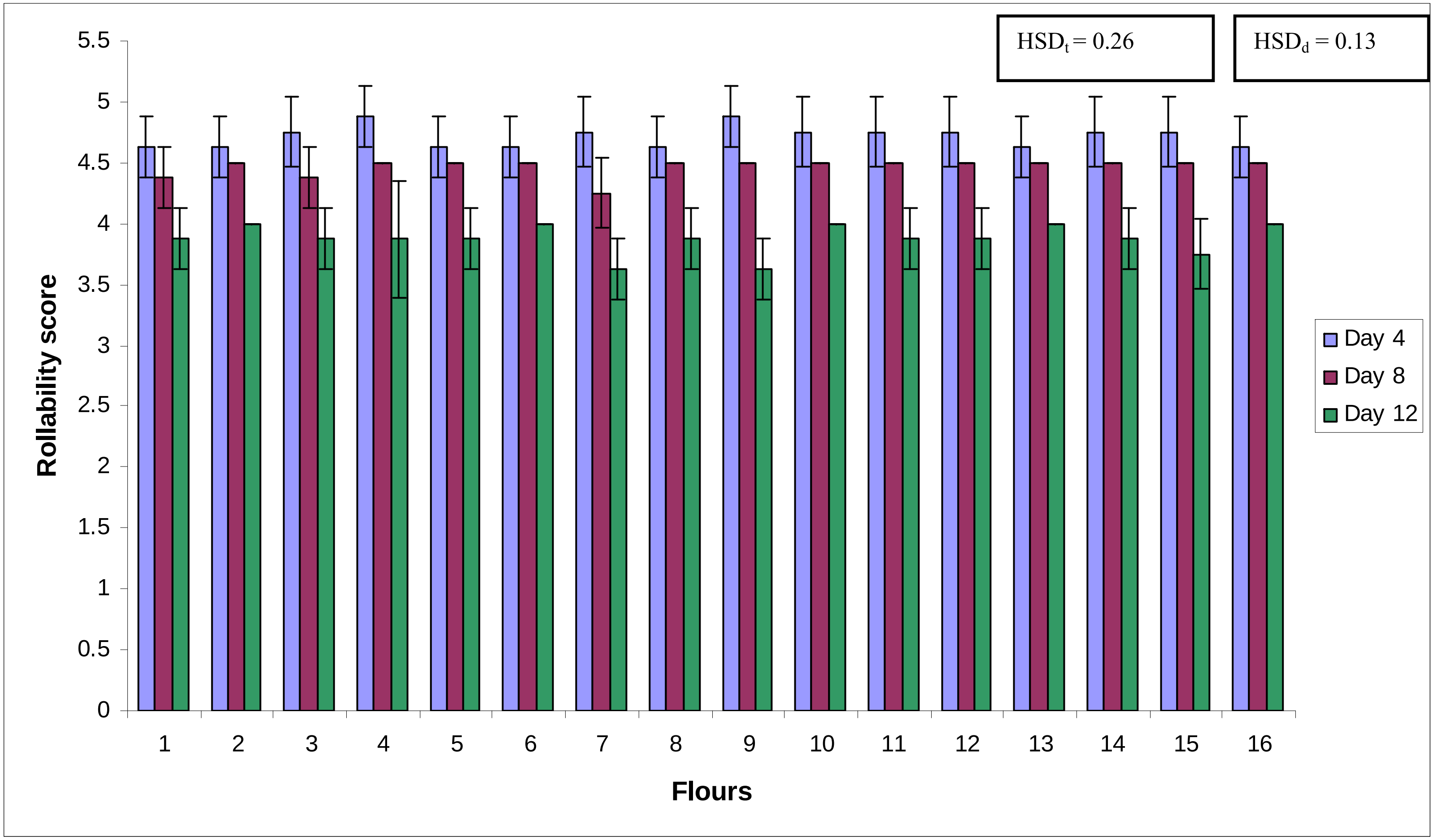

Fig. C2. Effect of storage time on rollability score. HSDt is for treatment, HSDd is for storage time.

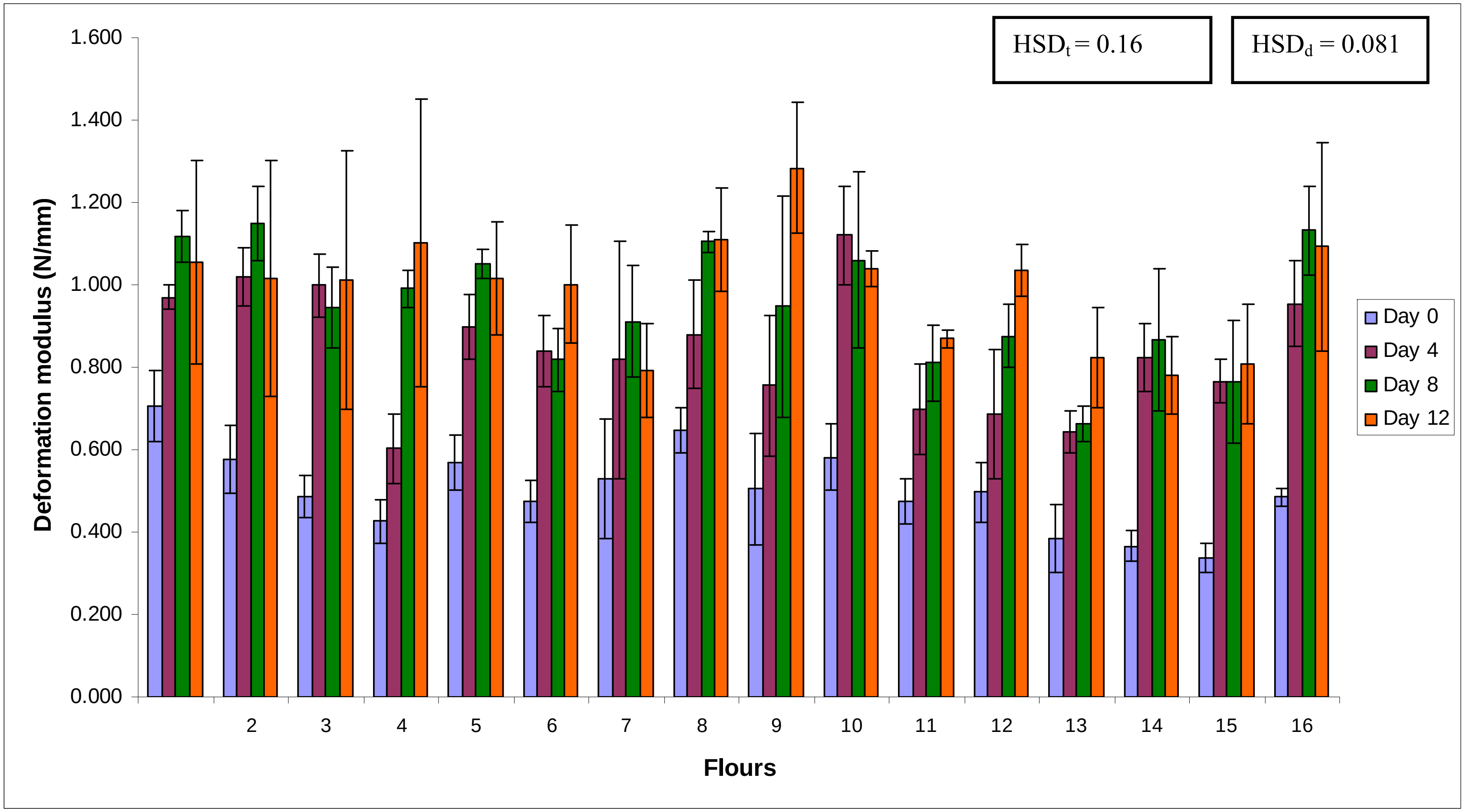

Fig. C3. Effect of storage time on deformation modulus (two-dimensional extensibility). HSDt is for treatment, HSDd is for storage time

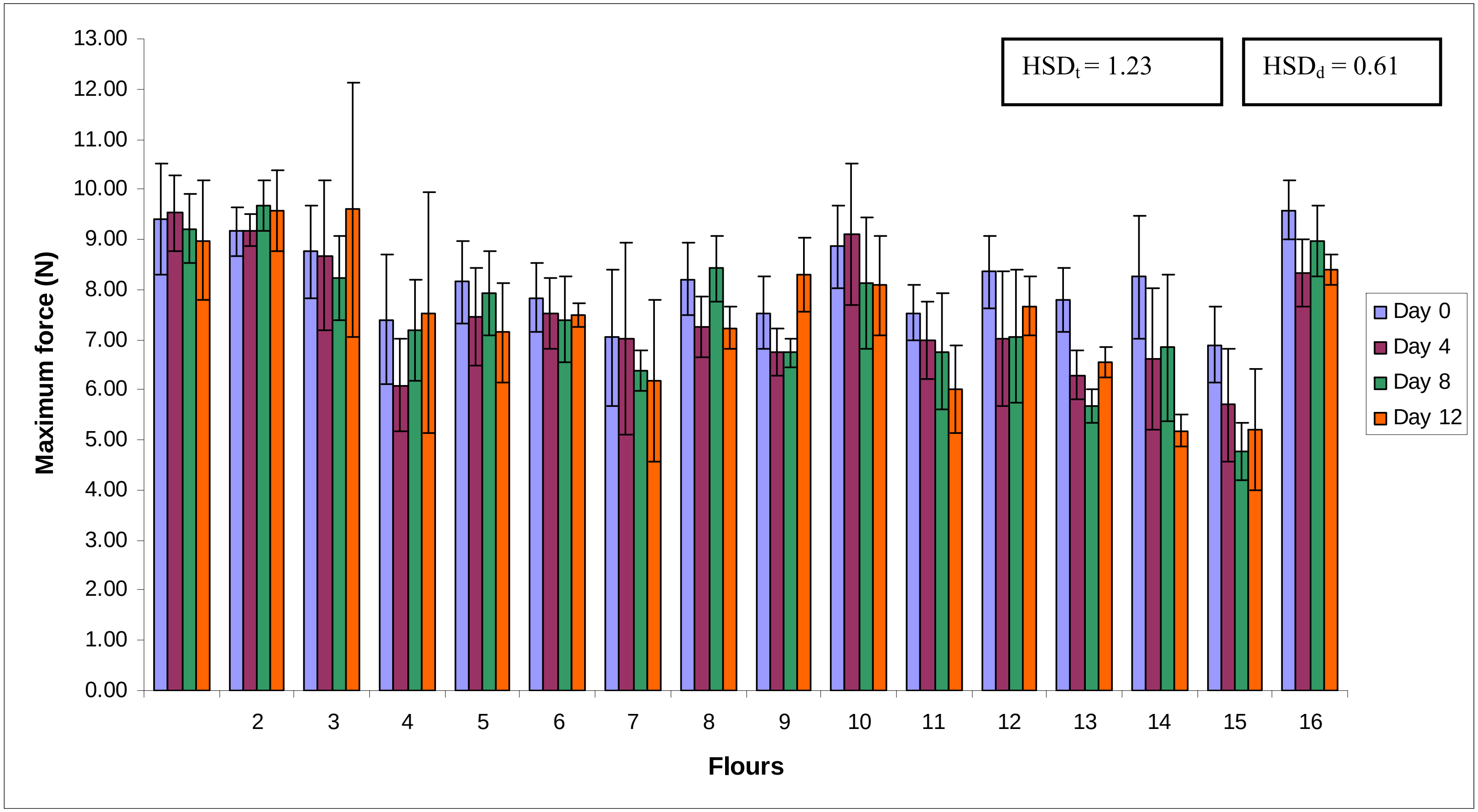

Fig. C4. Effect of storage time on maximum force (two-dimensional extensibility). HSDt is for treatment, HSDd is for storage time.

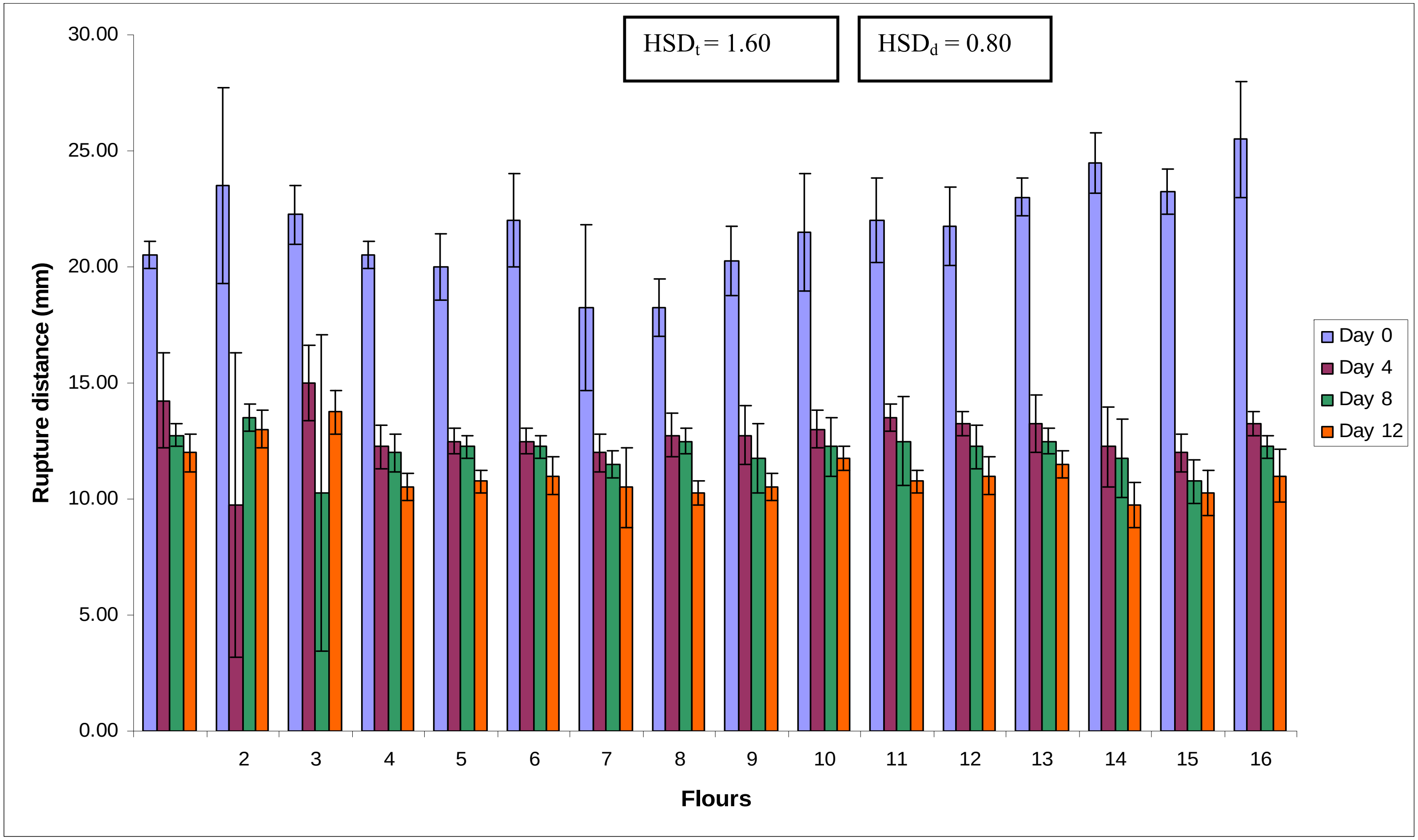

Fig. C5. Effect of storage time on rupture distance (two-dimensional extensibility). HSDt is for treatment, HSDd is for storage time

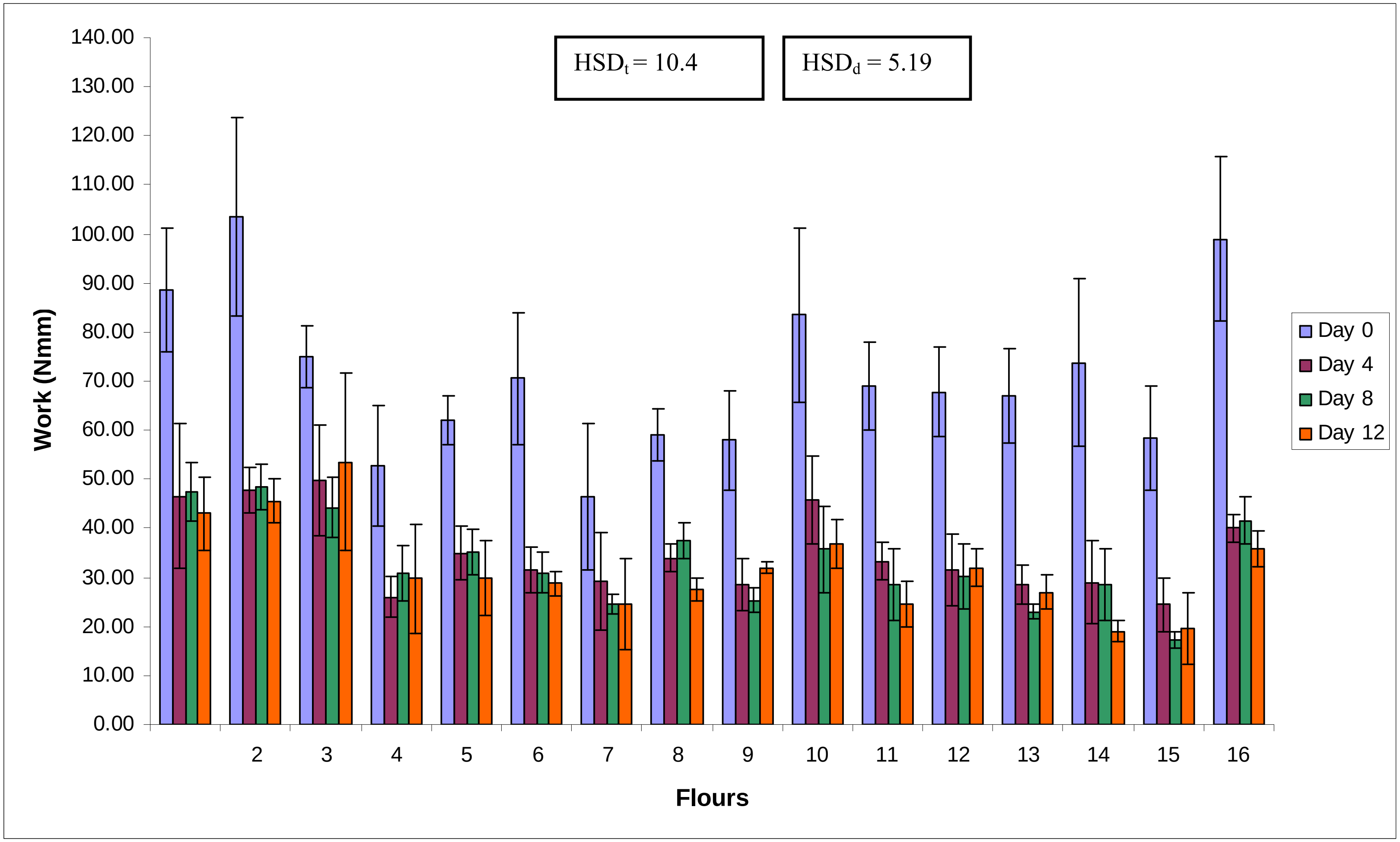

Fig. C6. Effect of storage time on work (two-dimensional extensibility). HSDt is for treatment, HSDd is for storage time

TABLE C3

Correlations of dough objective test using a texture analyzer, sedimentation height and other dough properties

Variables			**Farinograph**				**Mixograph**	
	Sedimentation height	**Water absorption**	**Development time**	**Stability**	**Breakdown time**	**Tolerance index**	**Mix-time**	**Mix-tolerance**
Sedimentation height	-	-0.19	0.35	0.57*	0.58*	-0.55*	0.42	0.43
<u>Dough extensibility</u>								
Resistance to extension	0.53*	0.13	0.67**	0.75**	0.75**	-0.77**	0.73**	0.69**
Extensibility	-0.54*	-0.001	-0.55*	-0.50*	-0.55*	0.66**	-0.61*	-0.60*
<u>Gluten extensibility</u>								
Resistance to extension	0.48	-0.06	0.54*	0.46	0.50*	-0.64**	0.64**	0.53*
Extensibility	-0.38	0.04	-0.46	-0.42	-0.38	0.51	-0.49	-0.41
<u>TPA</u>								
Hardness	-0.01	-0.65**	-0.39	-0.37	-0.34	0.25	-0.16	-0.23
Cohesiveness	0.71**	-0.16	0.39	0.55*	0.54*	-0.53*	0.48	0.42
Adhesiveness	-0.17	0.03	-0.43	-0.48	-0.59*	0.51*	-0.29	-0.31
Springiness	0.52*	0.27	0.60*	0.78**	0.71**	-0.69**	0.71**	0.65**
<u>Stress Relaxation</u>								
Equilibrium stress	0.57*	0.15	0.68**	0.79**	0.75**	-0.76**	0.84**	0.79**
Relaxation time	0.21	0.42	0.30	0.45	0.40	-0.33	0.31	0.34
k1	0.54*	0.20	0.57*	0.80**	0.70**	-0.74**	0.73**	0.72**
k2	0.53*	0.18	0.62*	0.75**	0.72**	-0.66**	0.76**	0.73**

** Correlation is significant at the 0.01 level (P<0.01)

* Correlation is significant at the 0.05 level (P<0.05)

TABLE C4
Data of tortilla quality validation – Observed (from WQC, 2008) and predicted parameters

	Diameter (mm)		Specific volume (cm3/g)		Deformation modulus (N/mm)		Maximum force (N)		Work (Nmm)	
Flours	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
1	156	158	1.5	1.2	0.7	0.6	10.2	9.5	97.2	76.7
2	165	166	1.6	1.3	0.7	0.6	7.9	9.7	59.9	82.1
3	160	152	1.5	1.1	0.7	0.7	9.9	10.3	95.6	77.6
4	171	165	1.8	1.3	0.6	0.6	7.7	8.5	57.9	64.8
5	157	151	1.5	1.1	0.7	0.8	9.2	10.3	77.7	78.5
6	134	115	1.2	0.4	0.7	1.2	12.1	18.1	142.4	122.1
7	153	151	1.4	1.1	0.6	0.8	9.6	9.6	99.6	74.3
8	149	136	1.3	1.1	0.8	0.7	12.3	9.6	140.9	71.6
9	174	169	1.8	1.4	0.6	0.5	7.4	8.6	66.4	75.2
10	151	137	1.4	0.7	0.8	1.1	11.2	13.5	118.6	84.4
11	155	150	1.4	1.1	0.7	0.7	11	8.6	121.5	57.8
12	173	172	1.6	1.5	0.6	0.5	8	7.4	76.4	46.0
13	170	170	1.8	1.5	0.7	0.5	8.1	7.9	58.7	64.6
14	170	162	1.9	1.3	0.7	0.6	7.5	8.8	51	67.9
15	165	165	1.8	1.4	0.7	0.5	8.5	8.2	64.2	61.8
16	165	161	1.7	1.3	0.6	0.6	8.4	9.5	64.9	80.7
17	165	157	1.6	1.3	0.7	0.6	8.6	8.9	73.7	68.9
18	171	169	1.8	1.4	0.6	0.5	7.1	8.7	51.2	76.5

Table C5
Comparison between stress relaxation method 1 (whole dough ball) and stress relaxation method 2 (sheeted dough) *

Flours	Method 1				Method 2			
	Equilibrium modulus (Pa)	Relaxation time (sec)	k1 (sec)	k2	Equilibrium modulus (Pa)	Relaxation time (sec)	k1 (sec)	k2
R TX01A5936	26.02 a	1.64 a	0.794 a	1.071 a	3.95 a	0.80 b	1.09 a	1.24 a
	(0.34)[1]	(0.10)	(0.04)	(0.004)	(0.75)[1]	(0.36)	(0.003)	(0.02)
W TX01A5936	33.05 b	1.48 a	0.888 a	1.094 b	3.20 a	0.20 a	1.14 b	1.22 a
	(0.12)	(0.04)	(0.043)	(0.002)	(0.13)	(0.0)	(0.02)	(0.017)
R Hard white wheat	31.22 a	1.84 a	1.035 a	1.092 a	1.20 a	0.40 b	1.0 a	1.08 a
	(0.10)	(0.06)	(0.04)	(0.002)	(0.10)	(0.03)	(0.028)	(0.014)
W Hard white wheat	38.88 b	1.61 a	1.054 a	1.111 b	1.88 b	0.31 a	1.14 b	1.14 b
	(0.17)	(0.26)	(0.070)	(0.002)	(0.03)	(0.02)	(0.008)	(0.004)
R TAM 111	19.98 a	1.64 a	0.785 a	1.060 a	0.92 a	0.87 b	0.91 a	1.11 a
	(0.16)	(0.08)	(0.04)	(0.002)	(0.31)	(0.05)	(0.002)	(0.008)
W TAM 111	28.80 b	1.43 a	0.875 a	1.084 b	1.67 b	0.26 a	1.18 b	1.11 a
	(0.23)	(0.18)	(0.045)	(0.004)	(0.08)	(0.10)	(0.022)	(0.003)
R TAM 401	24.18 a	1.73 b	0.793 a	1.070 b	1.23 a	0.94 b	1.23 b	1.09 a
	(0.10)	(0.02)	(0.003)	(0.001)	(0.13)	(0.27)	(0.075)	(0.012)
W TAM 401	23.97 a	1.39 a	0.806 a	1.065 a	1.23 a	0.29 a	1.0 a	1.09 a
	(0.02)	(0.02)	(0.021)	(0.002)	(0.13)	(0.02)	(0.002)	(0.002)
R TX01V5314	31.67 a	1.82 a	0.998 a	1.091 a	1.62 a	0.75 b	1.36 b	1.14 b
	(0.11)	(0.09)	(0.03)	(0.002)	(0.15)	(0.04)	(0.057)	(0.013)
W TX01V5314	36.10 b	1.70 a	1.118 b	1.103 b	1.37 a	0.27 a	1.18 a	1.10 a
	(0.21)	(0.14)	(0.010)	(0.005)	(0.08)	(0.06)	(0.063)	(0.001)

1- Standard deviation

* Means followed by the same letter in the same column between samples (refined and whole wheat) are not significantly different (P≤ 0.05)

TABLE C6

Shelf stability study: TX01A5936*

Parameter	Storage time (days)- Refined wheat flour tortilla					Storage time (days) – Whole wheat flour tortilla				
	0	1	4	8	14	0	1	4	8	14
Subjective rollability	5 (0.0)[1]	5 (0.0)	4.5 (0.0)	4.1 (0.20)	3.3 (0.27)	5 (0.0)	4.5 (0.0)	3.3 (0.26)	3 (0.32)	2.3 (0.27)
<u>Two-dimensional extensibility</u>										
Deformation modulus (N/mm)	0.52a,b (0.06)	0.42a (0.19)	0.62a,b (0.19)	0.64a,b (0.17)	0.71b (0.15)	0.59a (0.08)	0.60a (0.17)	0.76a,b (0.12)	0.80a,b (0.13)	0.85b (0.13)
Maximum force (N)	7.22b (0.97)	6.99a,b (1.78)	6.23a,b (1.36)	5.07a (0.60)	5.46a,b (0.70)	6.22b (0.44)	5.21a (0.57)	5.14a (0.57)	5.23a (0.73)	5.08a (0.55)
Rupture distance (mm)	18.98d (0.86)	15.90c (1.29)	11.18b (1.22)	9.78a,b (1.98)	8.77a (1.46)	16.08d (0.84)	12.16c (0.62)	9.49b (1.40)	9.15a,b (0.67)	7.59a (0.87)
Work (Nmm)	52.59c (7.94)	38.72b (10.02)	25.50a (6.11)	18.72a (4.51)	19.82a (2.09)	38.08c (4.67)	22.82b (2.79)	19.23a,b (2.84)	18.68a,b (2.94)	17.22a (2.66)
<u>One-dimensional extensibility</u>										
Deformation modulus (N/mm)	0.35a (0.09)	0.57a (0.17)	0.81a,b (0.38)	1.11b (0.12)	1.13b (0.49)	0.45a (0.12)	0.56a (0.16)	0.85a,b (0.30)	1.13b (0.27)	1.02b (0.32)
Maximum force (N)	2.09a (0.94)	1.92a (0.26)	1.93a (0.59)	2.34a (0.46)	2.07a (0.53)	2.25a (0.69)	2.02 (0.22)	2.31a (0.35)	2.48a (0.32)	2.29a (0.47)
Rupture distance (mm)	10.22c (3.13)	4.95b (0.56)	3.21a,b (0.36)	2.81a,b (0.39)	2.00a (0.47)	5.74d (0.52)	3.61c (0.51)	2.16b (0.35)	1.99a,b (0.15)	1.54a (0.25)
<u>Stress relaxation</u>										
Percent stress relaxation (%)	85.27a (6.56)	79.41a (11.27)	69.54a (7.66)	77.65a (19.38)	69.48a (7.22)	75.32a (8.27)	75.44a (6.33)	70.02a (4.19)	75.52a (13.20)	66.55a (4.68)

[1] Standard deviation

*Means followed by the same letter in the same row are not significantly different between samples ($P \leq 0.05$)

TABLE C7

Shelf stability study: Hard white wheat *

Rheological parameter	Storage time (days)- Refined wheat flour tortilla					Storage time (days) – Whole wheat flour tortilla				
	0	1	4	8	14	0	1	4	8	14
Subjective rollability	5 (0.0)[1]	5 (0.0)	4.5 (0.0)	4.3 (0.0)	3.7 (0.0)	5 (0.0)	4.5 (0.0)	3.5 (0.45)	3.1 (0.20)	3.1 (0.20)
Two-dimensional extensibility										
Deformation modulus (N/mm)	0.65a (0.20)	0.61a (0.20)	0.78a (0.13)	0.80a (0.19)	0.82a (0.12)	0.63a (0.08)	0.70a,b (0.21)	0.89a,b (0.16)	0.88a,b (0.12)	0.92b (0.19)
Maximum force (N)	9.67b (1.09)	8.53a,b (1.32)	7.80a (0.97)	8.28a,b (1.15)	7.74a (0.46)	6.86a (0.87)	6.7a (0.72)	6.19a (0.86)	5.88a (0.62)	5.56a (0.92)
Rupture distance (mm)	20.41c (1.76)	15.41b (1.29)	11.42a (2.12)	11.19a (1.92)	9.83a (1.00)	16.11c (1.07)	13.18b (1.28)	9.71a (1.33)	9.45a (0.53)	7.91a (1.29)
Work (Nmm)	79.49c (7.04)	48.38b (10.13)	33.65a (7.59)	34.44a (8.67)	31.06a (2.77)	44.13c (7.41)	33.34b (4.45)	23.8a (4.72)	22.80a (2.88)	20.09a (4.12)
One-dimensional extensibility										
Deformation modulus (N/mm)	0.46a (0.08)	0.74a,b (0.21)	1.07b,c (0.37)	1.37c (0.26)	1.40c (0.32)	0.46a (0.14)	0.64b (0.13)	0.89a,b (0.33)	1.23b,c (0.33)	1.39c (0.42)
Maximum force (N)	2.68a (0.97)	2.75a (0.18)	2.76a (0.60)	3.30a (0.24)	3.18a (0.46)	2.21a (0.71)	2.30a (0.19)	2.47a (0.46)	2.66a,b (0.26)	3.22b (0.28)
Rupture distance (mm)	12.89c (0.59)	6.67b (1.39)	3.83a (0.69)	3.63a (0.56)	3.08a (0.55)	5.98c (1.34)	4.20b (0.55)	2.64a (0.21)	2.15a (0.17)	1.98a (0.16)
Stress relaxation										
Percent stress relaxation (%)	81.86b (3.70)	79.25b (10.49)	70.05a,b (4.27)	62.05a (4.31)	68.33a,b (7.47)	76.14a (1.68)	77.76a (6.10)	69.53a (4.48)	74.41a (11.20)	67.85a (4.21)

[1] Standard deviation

*Means followed by the same letter in the same row are not significantly different between samples ($P \leq 0.05$)

TABLE C8

Shelf stability study: TAM 111*

Rheological parameter	Storage time (days)- Refined wheat flour tortilla					Storage time (days) – Whole wheat flour tortilla				
	0	1	4	8	14	0	1	4	8	14
Subjective rollability	5 (0.0)[1]	5.0 (0.0)	4.5 (0.0)	3.2 (0.68)	1.8 (0.26)	5 (0.0)	4.5 (0.0)	2.3 (0.52)	1.5 (0.32)	1.1 (0.20)
Two-dimensional extensibility										
Deformation modulus (N/mm)	0.44a (0.09)	0.54a (0.20)	0.52a (0.09)	0.62a,b (0.12)	0.75b (0.07)	0.56a (0.10)	0.57a (0.12)	0.69a,b (0.14)	0.75a,b (0.09)	0.86b (0.14)
Maximum force (N)	6.31b (0.63)	5.28a (0.74)	4.34a (0.59)	4.36a (0.46)	4.42a (0.48)	5.24b (0.62)	4.23a (0.49)	3.91a (0.57)	3.74a (0.45)	4.07a (0.75)
Rupture distance (mm)	18.78c (1.77)	13.09b (1.28)	10.01a (2.09)	9.29a (1.50)	7.67a (1.55)	14.23c (1.06)	11.13b (0.83)	8.26a (1.78)	7.66a (1.32)	6.32a (1.29)
Work (Nmm)	44.12c (9.14)	24.30b (2.88)	16.11a (4.23)	14.97a (1.41)	14.76a (2.37)	27.9c (3.40)	16.93b (2.90)	12.59a (2.50)	12.14a (2.24)	11.71a (2.40)
One-dimensional extensibility										
Deformation modulus (N/mm)	0.33a (0.07)	0.59a,b (0.10)	0.86b,c (0.35)	1.06c (0.13)	1.13c (0.33)	0.45a (0.19)	0.56a,b (0.18)	0.81a,b (0.33)	1.04b (0.28)	1.02b (0.49)
Maximum force (N)	1.84a (0.83)	1.74a (0.22)	1.94a (0.27)	1.76a (0.39)	1.95a (0.36)	2.19a (0.81)	2.02a (0.29)	2.45a (0.21)	2.27a (0.41)	2.37a (0.24)
Rupture distance (mm)	6.49c (1.39)	3.05b (0.39)	2.20a,b (0.45)	1.78a (0.42)	1.35a (0.24)	3.94c (0.78)	3.08b (0.35)	1.96a (0.34)	1.55a (0.23)	1.24a (0.09)
Stress relaxation										
Percent stress relaxation (%)	83.27b (10.38)	79.67b (9.03)	68.93a,b (5.91)	62.43a (4.74)	61.62a (7.26)	71.60a (7.74)	75.15a (9.15)	68.41a (4.04)	72.08a (12.19)	63.95a (4.01)

[1] Standard deviation

*Means followed by the same letter in the same row are not significantly different between samples ($P \leq 0.05$)

TABLE C9

Shelf stability study: TAM 401*

Rheological parameter	Storage time (days)- Refined wheat flour tortilla					Storage time (days) – Whole wheat flour tortilla				
	0	1	4	8	14	0	1	4	8	14
Two-dimensional extensibility	5 (0.0)[1]	5 (0.0)	4.5 (0.0)	4.2 (0.3)	3.3 (0.26)	5 (0.0)	4.5 (0.0)	3.1 (0.38)	2.8 (0.52)	2.6 (0.2)
Deformation modulus (N/mm)	0.49a (0.15)	0.48a (0.25)	0.64a,b (0.26)	0.62a,b (0.11)	0.82b (0.10)	0.56a (0.11)	0.51a,b (0.15)	0.64a,b (0.18)	0.75b (0.10)	0.73b (0.04)
Maximum force (N)	6.88b (0.45)	6.55a,b (0.74)	5.87a,b (0.80)	5.39a (1.01)	6.18a,b (1.07)	5.34b (0.53)	4.67a,b (0.69)	4.13a (0.65)	4.29a,b (0.87)	3.86a (0.23)
Rupture distance (mm)	19.45c (1.91)	15.10b (1.34)	11.40a (3.21)	10.19a (2.30)	8.84a (1.58)	15.30d (0.64)	12.21c (0.54)	9.36b (2.38)	8.47a,b (1.01)	6.97a (1.33)
Work (Nmm)	51.67c (7.29)	35.27b (3.95)	24.69a (7.24)	20.33a (5.39)	23.92a (5.04)	28.87c (4.62)	20.06b (4.12)	14.64a,b (3.87)	15.20a,b (3.20)	12.34a (1.06)
One-dimensional extensibility										
Deformation modulus (N/mm)	0.40a (0.10)	0.56a (0.14)	0.80a,b (0.35)	1.02b (0.20)	1.07b (0.37)	0.43a (0.16)	0.51a (0.13)	0.66a,b (0.28)	1.02b (0.28)	1.01b (0.41)
Maximum force (N)	2.09a (0.68)	1.95a (0.20)	1.97a (0.53)	2.00a (0.24)	2.28a (0.23)	2.03a (0.65)	1.70a (0.27)	1.84a (0.26)	1.94a (0.21)	2.28a (0.28)
Rupture distance (mm)	11.12c (3.26)	5.97b (1.43)	3.75a,b (0.61)	2.73a (0.39)	2.47a (0.46)	4.86c (0.95)	3.12b (0.52)	2.12a (0.57)	1.81a (0.24)	1.65a (0.11)
Stress relaxation										
Percent stress relaxation (%)	82.37b (10.58)	81.52b (10.17)	69.54a (6.78)	66.40a (6.72)	66.35a (6.20)	76.37a (9.66)	74.73a (5.86)	67.81a (4.48)	73.81a (13.97)	63.29a (8.12)

[1] Standard deviation

*Means followed by the same letter in the same row are not significantly different between samples (P≤ 0.05)

TABLE C10
Shelf stability study: TX01V5314*

Rheological parameter	Storage time (days)- Refined wheat flour tortilla					Storage time (days) – Whole wheat flour tortilla				
	0	1	4	8	14	0	1	4	8	14
Two-dimensional extensibility	5 (0.0)[1]	5 (0.0)	4.5 (0.0)	4.3 (0.27)	3.6 (0.2)	5 (0.0)	4.5 (0.0)	3.6 (0.20)	3.7 (0.26)	3.4 (0.2)
Deformation modulus (N/mm)	0.54a (0.08)	0.52a (0.18)	0.60a,b (0.17)	0.68a,b (0.13)	0.79b (0.14)	0.63a (0.10)	0.64a (0.15)	0.69a (0.14)	0.81a (0.09)	0.78a (0.13)
Maximum force (N)	8.1a (1.09)	7.76a (0.81)	6.94a (1.21)	7.23a (1.24)	6.84a (0.63)	6.52b (0.42)	6.56b (0.87)	5.92a,b (0.31)	5.88a,b (0.90)	5.19a (0.78)
Rupture distance (mm)	20.76c (1.57)	16.29b (1.51)	12.51a (2.93)	11.64a (2.23)	9.64a (1.38)	16.23d (1.18)	13.66c (0.74)	10.76b (2.14)	9.81a,b (1.16)	8.32a (1.46)
Work (Nmm)	68.99c (13.83)	47.98b (6.74)	33.58a (9.80)	32.22a (7.94)	28.23a (2.52)	39.32b (3.73)	33.91b (5.71)	24.51a (2.45)	23.34a (5.02)	19.34a (3.46)
One-dimensional extensibility										
Deformation modulus (N/mm)	0.42a (0.07)	0.59a,b (0.14)	0.79b,c (0.24)	1.03c,d (0.12)	1.15d (0.33)	0.47a (0.18)	0.61a,b (0.23)	0.75a,b (0.25)	1.04b (0.22)	1.01b (0.45)
Maximum force (N)	2.13a (0.60)	2.10a (0.23)	2.27a (0.24)	2.44a (0.24)	2.4a (0.59)	2.36a (0.88)	2.26a (0.36)	2.26a (0.21)	2.48a (0.31)	2.4a (0.24)
Rupture distance (mm)	11.77c (2.94)	6.8b (1.48)	4.76a,b (0.63)	3.60a (0.39)	3.06a (0.97)	5.64c (1.00)	4.44b (0.90)	2.92a (0.48)	2.51a (0.43)	1.84a (0.32)
Stress relaxation										
Percent stress relaxation	85.30b (7.68)	77.90a (11.67)	72.67a (5.94)	71.40a (3.33)	71.51a (2.43)	75.15a (6.09)	71.93a (6.82)	68.54a (5.32)	76.62a (13.37)	62.01a (9.44)

[1] Standard deviation
*Means followed by the same letter in the same row are not significantly different between samples (P≤ 0.05)

VITA

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